Introduction and Motivation

This renewal proposal requests funds to continue operation of the Basic Plasma Science Facility (BaPSF) at the University of California, Los Angeles (UCLA), and to support the vigorous research program of the BaPSF scientific staff, as well as to continue the improvements in scientific instrumentation required to maintain worldwide leadership in fundamental plasma research. BaPSF provides national and international scientists access to unique research devices and diagnostic tools that permit the exploration of a wide range of fundamental plasma problems that impact topics at the frontiers of fusion, space science and plasma technology. The broad parameter ranges accessible in the plasma devices operated at BaPSF allow studies that span microscopic phenomena on the fast electron time scales (e.g., electron plasma waves, cyclotron radiation) to the slow time scales characteristic of plasma transport driven by drift-wave turbulence and long wavelength magnetic fluctuations. This extensive basic plasma research capability in a single laboratory setting is not available anywhere else, but examples of analogous user facilities exist in other scientific disciplines. Qualified researchers and research teams from universities, national laboratories and industry can perform experiments at BaPSF, free of charge, upon approval of their proposals by a Scientific Council composed of senior scientists broadly representative of the plasma community.

Over the past 5 years, the scientific activities at BaPSF involve individuals affiliated with 18 different institutions: 11 professors, 12 Ph.D. scientists, 15 graduate students and 12 undergraduate students. The research modalities accommodate a range of options: single-user operation, theory-driven investigations, and topical campaigns. Single users consist of small groups who pursue a well-defined theme that can be brought to a successful completion without major involvement from the BaPSF scientific staff. Theory-driven studies involve important problems suggested by individuals who are not directly qualified to perform experiments in a complex hardware environment, but who define the scientific goals and participate in the data gathering, analysis and interpretation of experiments conducted by the BaPSF staff. This mode requires extensive support by the BaPSF scientific and technical staff and often involves UCLA graduate students. Topical campaigns consist of a large and diverse group of researchers from various institutions who pursue a common set of problems of contemporary interest. The campaigns involve experimentalists, theoreticians, modelers, and also the BaPSF scientific and technical staff. Over the past (five year) funding cycle these various modes of operation have resulted in 46 reviewed publications and 39 invited presentations (listed in Appendix) Selected highlights from these studies are presented later.

The BaPSF plasma devices provide effective platforms for the training of graduate students because of their optimum, mid-scale size. The devices and diagnostic tools available at the BaPSF are sufficiently large and sophisticated so as to provide exposure to frontier developments that require learning to work in a team environment. These are valuable experiences not commonly available to graduate students in small, single-PI laboratories. Yet, the size of the BaPSF operation is small enough for students to obtain individual hands-on experience not available at facilities with large fusion devices. Over the past funding cycle, 11 students have earned Ph.D.s based on work performed at the BaPSF, and 3 have completed M.S. degrees.

The reliable and flexible operation of the BaPSF, by a dedicated and experienced staff, also provides a fertile environment for the development of young faculty by allowing them to focus entirely on scientific research. Over the past funding cycle, Prof. C. Niemann (UCLA) performed experimental studies at BaPSF that culminated in his receiving tenure. Prof. G. Howes (U. Iowa) also received tenure during this period with a research portfolio that included BaPSF experiments. Currently, J.

Bortnik (UCLA) is taking advantage of the BaPSF to develop a similar career trajectory. It is expected that other young faculty members will similarly benefit from the BaPSF capabilities during the next 5 years of operation.

An essential element leading to the successful operation of BaPSF is the vigorous research program pursued by the scientific staff of the facility. The results obtained by these researchers expand the frontiers of the field, explore the limits of the hardware, and pave new avenues for BaPSF users to pursue. A scientific research program led by the BaPSF staff is part of this proposal.

Our vision for the future of BaPSF is to create a facility with enough flexibility to address frontier scientific issues that cut across multiple disciplines within plasma science. Such issues as; Alfvénic shocks, 3D reconnection, turbulence and transport, radiation belt physics, solar and stellar wind turbulence, and solar atmospheric transport and turbulence. We plan to accomplish this by providing a range of well-diagnosed research devices than span a parameter space of sufficient breadth to address many problems of current interest, an infrastructure that allows easy and interchangeable access to all devices, and a management structure that promotes cooperation between experimentalists, theoreticians and computer modelers.

Organization and Operation

Currently the BaPSF operates five plasma devices having complementary capabilities that meet different research, development and educational needs of the user community. The centerpiece is the Large Plasma Device (LAPD). The LAPD generates highly reproducible and quiescent magnetized plasma columns 18 meters in length, once per second, over a continuous period of approximately three months. Details of the operational parameters are given in the Appendix (table A1). This linear device has been in operation for nearly 20 years and undergoes continuous improvements to provide the world's most advanced research tool for basic plasma science. This is the primary device used in implementing the facility research programs. An upgrade to the LAPD is planned as part of the proposed work, adding a new plasma source that will increase uptime and significantly expand the range of plasma parameters accessible using the device. The Small Plasma Device (SMPD) is a low-field plasma chamber four meters in length used to develop probes, test new diagnostic concepts, and perform research on topics that do not require the high-performance plasma parameters available in the LAPD. The Enormous Toroidal Plasma Device (ETPD) is a large, toroidal plasma chamber with a major radius of 5 meters in development as a research tool. The ETPD is presently used to test new cathode concepts for generating long, high-density plasma columns, and is potentially of great interest to fusion, space, solar and astrophysical researchers. Over the past 5 years, a graduate student is completed a Ph.D. dissertation related to the plasma processes involved in the formation of the ETPD plasma column. A plasma processing device, donated by industry, provides a platform for the study of low temperature plasmas and the properties of RF sheaths. Two graduate students have used this tool to complete Ph.D. studies related to the energetic ion distribution functions formed in these environments. The diagnostics and experience obtained using this tool will be beneficial in a forthcoming campaign related to RF antennas used in fusion plasmas. Finally, a small, dedicated machine with a helicon-generated plasma is used to train high school teachers and students enrolled in the LAPTAG (Los Angeles Physics Teachers Alliance Group) outreach program [1]. Work done in this device by the high school students and teachers is routinely presented at meetings and some results have been published.

During the last funding cycle LAPD operated in a reliable, steady-state research mode. On average, the machine was available for scientific research over 70 percent of the time, exceeding the target of 60 percent availability set in the original facility proposal. On average, over the last three years (2012-2014) the LAPD was available 282 days out of the year (80% uptime). Maintenance (primarily the periodic replacement of the Barium Oxide cathode coating) accounted for 14% of the downtime. Of the 282 days of operation, 64% of the run time was allocated to external users with the remaining 36% allocated to the local group; the original facility proposal dictated a 50-50 split between external users and the local group.

Management Structure

The goal of facility management is to maximize scientific productivity while providing users dependable and convenient access to all facility resources. For management purposes facility users are divided into two groups: the local group and external users. For this renewal proposal, the local group consists of four BaPSF Principal Investigators: T. Carter, W. Gekelman, G. Morales, and S. Vincena together with the postdoctoral scientists and graduate students associated with their research. External users are all other researchers, including those resident at UCLA, who have no responsibility for BaPSF operations.

For this renewal, BaPSF will led by a director, Troy Carter, who will be responsible for the operation of the facility and supervision of facility personnel, the overall coordination of the interaction with the user groups, and reporting to funding agencies. Walter Gekelman had been director of BaPSF since its inception in 2000 and led the team that designed and constructed the LAPD device. For the proposed renewal period, Prof. Gekelman will take on the role of Associate Director for Project Development and will lead hardware development for the facility, in particular the major cathode upgrade project described below. Dr. Vincena helps the director coordinate facility use with the efforts of the local research group and is responsible for the generation of reliable plasma conditions in LAPD. Prof. Morales oversees the connection of the facility experimental program to the broad plasma science community and monitors the overall scientific directions. The director is assisted by a staff consisting of a technical coordinator and scientific liaisons. The technical coordinator (Zoltan Lucky) is responsible for the overall maintenance of the plasma devices and laboratory equipment, including probes, probe drives and electronics. The scientific liaisons (Drs. Bart Van Compernolle and Shreekrisna Tripathi) assist external users in operating the LAPD and in implementing their experimental objectives. The facility has a full time Project Scientist/Engineer (Dr. Pat Pribyl), three full time laboratory technicians and an administrative assistant.

Facility Access

Individuals interested in performing experiments at the facility submit a short white paper to the director outlining a proposed experiment. The director consults with the local group concerning the feasibility of implementing the proposed experiment. The director reserves the right to refuse any experiments deemed likely to cause irreparable or significant damage to the infrastructure. For each feasible experiment, the director obtains an evaluation of the scientific quality and recommendation of the priority of the proposed experiment from the Scientific Council. For each approved white paper, the director assigns a scientific liaison to be the contact person with the proposer. Most external users submit proposals to the funding agency of their choice where they are reviewed according to the individual procedures of the agency. The scientific liaison aids in supplying any information needed to write a full proposal. The director includes a letter of support and a commitment to provide the machine time needed for the proposed experiment. Some users already have funding or do not require support, and thus proceed to access BaPSF resources directly upon approval.

When a user group arrives at the facility to conduct an experiment, they interface with the assigned scientific liaison. The liaison assists the user group with the use of facility assets in order to insure the safety of personnel, and to protect facility resources from improper use. The scientific liaison makes sure that the necessary facility equipment and diagnostics are available and operational at the required time, assists in the preparations for data acquisition and is on the floor with the user team to aid in the successful implementation of the research plan. After experimental data is acquired the liaison assists, if requested by the users, in local visualization and analysis of data, exportation of data and data backup.

Scientific Council

The scientific council gives advice and guidance to the BaPSF PIs on management and scientific issues. The council meets formally at the annual APS-DPP meeting to review progress, suggest improvements, and provide advice to the director concerning policy matters. Through email communications, the council reviews white papers and makes a recommendation to the director on granting facility access. The current membership of the council is: R. Berger (LLNL), B. Briezman (U. Texas), V. Chan (General Atomics), M. Koepke (WVU), S. Spangler (U. Iowa), and E. Zweibel (U. Wisconsin). Dr. Chan has recently retired from GA and will be cycling off the council. Normally, council membership is refreshed approximately every year by rotating out one member. New members are selected by the PIs upon the advice of the council and in consultation with the funding agencies. On July 20, 2015 the council visited UCLA to examine the status of the facility hardware and infrastructure, and to give advice on the preparation of this proposal.

Users Group

A BaPSF users group was created in 2013 to provide opportunities for BaPSF users to meet and discuss recent research and plans and a formal mechanism for users to provide feedback to the facility management. Prof. W Heidbrink (UC Irvine) served as the chair of the users group from inception until 2015, Dr. P. Colestock (LANL, retired) is the current chair of the Users group. The group met at the 2013 and 2014 APS DPP meetings and at UCLA April 20-21, 2015. A report generated by the Users group at the April 2015 meeting is included in the Appendix of this proposal. User group meetings will continue to occur yearly at APS DPP and biannually at UCLA.

Results from Prior Support

In this section we present highlights of selected research programs from both the external user groups and the local group. Details of research programs not covered here are included in the Appendix.

Research Highlights – External user groups:

Over the past 5 years, there have been six independent experimental user groups, seven theory-driven studies and three topical campaigns. The leaders of these various efforts and their affiliated institutions are listed here; highlights from 5 of these research programs follow.

Independent experimental user groups: 1) W. Heidbrink (University of California, Irvine); 2) C. Niemann (UCLA); 3) C. Kletzing, F. Skiff, G. Howes (University of Iowa); 4) M. Koepke (West Virginia University); (5) D. Bui, Y. Song (Tri Alpha Energy); (6) J. Judy (UCLA)

Theory-driven studies: 1) P. Colestock. M. Light (LANL); 2) J. Bortnik, R. Thorne (UCLA); 3) W. Daughton, J. Finn (LANL); (4) M. Kushner (U. Michigan); (5) D. D'Ippolito, J. Myra (Lodestar Corp); (6) A. Streltsov (Embry-Riddle University); (7) Li-Jen Chen (U. New Hampshire).

Campaigns: 1) "Fast-Ion Campaign", W. Heidbrink (University of California, Irvine); 2) "Auroral Physics Campaign", M. Koepke (West Virginia Univ.); 3) "Radiation-belt Physics Campaign", D. Papadopoulos, T. Antonsen (University of Maryland).

Generation of an Alfvénic shock using a high power laser (C. Niemann, C. Constantin, W. Gekelman, S. Vincena; A. Bondarenko, D. Schaeffer, E. Everson (grad students) (UCLA))

Magnetosonic collisionless shocks have been driven using an exploding laser-produce plasma in LAPD [2, 3]. This is the very first observation of collisionless shocks of cosmic relevance in a large, current-free laboratory plasma and the first experimental measurement of the shock formation time.

In these experiments a plastic target was irradiated with an energetic 200J laser beam from the new high-energy glass laser. A blow-off plasma was created that exploded at super-Alfvenic speed into an H^+ ambient plasma perpendicular to the 300 G external field.

Figure 1(a) shows stack plots of the measured magnetic field B_z/B_o for various distances x from the laser target. Each trace shows the typical signature of a diamagnetic laser plasma cavity, including an initial field compression followed by complete field expulsion. The magnetic pulse ahead of the cavity travels at 370 ± 20 km/s, which is super-Alfvénic ($M_A = 2.2 \pm 0.3$). The magnetic piston, i.e., the leading edge of the diamagnetic cavity, slows from 500 km/s near the target to 200 km/s in the center of the vessel. About 20 cm from the target, corresponding to $t\Omega_i = 1$, the magnetosonic pulse starts to steepen into a shock and to separate from the piston. The ramp continues to steepen up to a distance of 40 cm from the target, at which point the ambient plasma density drops sharply, and the shock dissipates. The measured field compression of $B_z/B_o \geq 2$ is consistent with the Rankine-Hugoniot jump conditions for a shock. In comparison with expansion into vacuum (Figure 1(b)), the field compression is significantly larger with the ambient plasma and the leading edge of the magnetic pulse expands faster, indicating that the pulse is carried by ambient ions, which have been accelerated by the piston. Simultaneously, the trailing edge of the pulse (i.e., the piston) moves much slower, indicative of energy transfer to the ambient plasma. The magnetic pulse in vacuum has a significantly shallower ramp due to fast ions that slip through the magnetic field, causing a weak magnetic disturbance ahead of the pulse. The spatial profile (Figure 1(c)) shows a ramp with a width of a few millimeters and a downstream region between the piston and the ramp of 30 ambient ion gyroradii. In comparison to earlier times before the shock is formed (blue dashed line in Figure 1(c)), the structure of the shock shows a significantly steeper and faster ramp, and a much broader, more

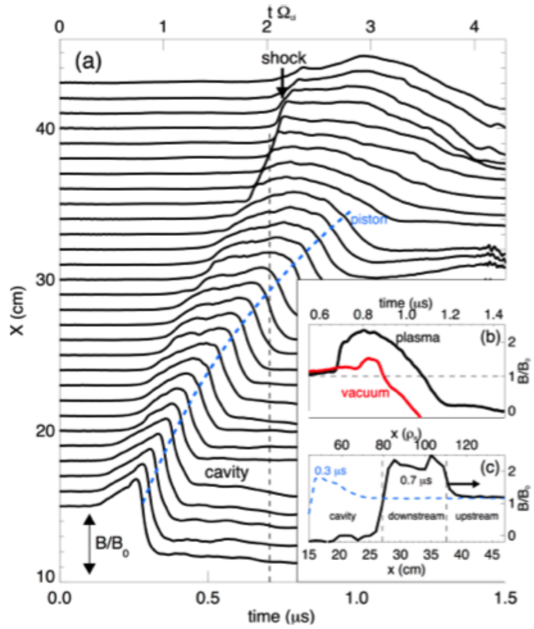

Figure 1: a) Magnetic stack plots of B_z as a function of time for various distances from the target. (b) Comparison of $B_z(t)$ at $x = 35$cm with (black) and without (red) the ambient plasma. (c) Structure of the pulse before ($t = 0.3$ μs) and after a shock is formed.

compressed pulse. In addition, the ramp of the shock steepens from an initial 40 c/ω_{pe} to less than 20 c/ω_{pe} at a distance of 40 cm from the target. The measured shock formation time around $t\Omega_i = 1$ is consistent with theoretical predictions, while the measured coupling parameter of $R_M/\rho_d = 1 \pm 0.1$ agrees well with the requirements found in hybrid simulations [4].

Resonant interactions between energetic electrons and whistler waves (J. Bortnik, R. Thorne, B. Van Compernolle; X. An (Graduate Student) (UCLA))

A major scientific problem of current interest is the determination of the dominant physical processes that drive the dynamic variability of the outer radiation belt [5, 6]. Resonant interactions between energetic electrons and whistler mode waves are thought to play an essential role [7, 8]. The ongoing theory-driven LAPD project, led by J. Bortnik, has a two-pronged approach; the resonant scattering of energetic electrons by whistler waves [9] is studied as well as the excitation of whistler waves by energetic electrons. The experimental work has been made possible by the development of a 10 cm diameter energetic electron beam source, with beam energies up to 5 keV.

In the past two years the experiment has focused on the excitation of whistler waves by energetic electrons under various plasma and beam conditions. A very recent result [10] is the excitation of discrete frequency chirping whistler waves, which have been observed in space for decades known as chorus waves, but have up to now never been observed in the laboratory. The experiment identifies stringent conditions under which the discrete frequency chirping is seen. There is a strong dependence on beam density, plasma density and the guide field profile and magnitude. Examples of the rich variety of beam-generated wave activity is displayed in the spectrograms in Fig. 2. The experiment allows, for the first time, to test under controlled conditions the leading theories in nonlinear whistler wave excitation. Manuscripts are also being prepared on the excitation of broad-

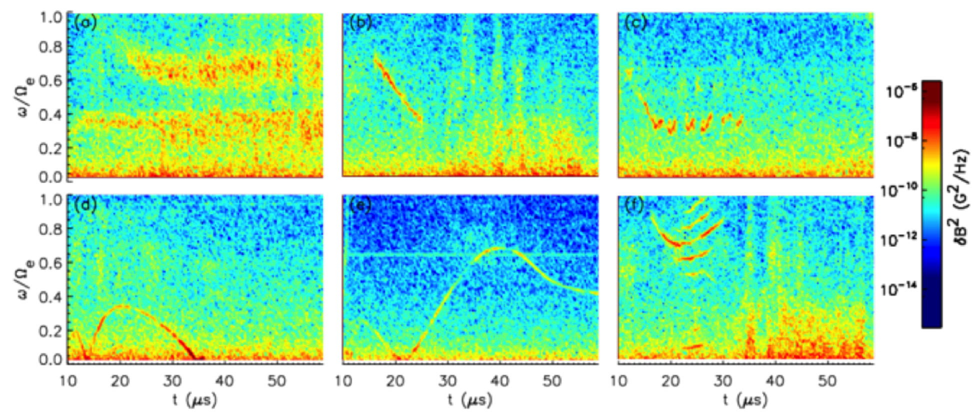

Figure 2: Examples of spectrograms of whistler wave excitation. (a) broadband waves, (b) falling tone, (c) multiple consecutive chirps, (d) double hook, (e) long rising and falling tone, (f) chirps at multiple frequencies simultaneously

band whistler waves (non-chirping). It is shown that energetic electrons resonantly excite whistler waves simultaneously through the Doppler shifted cyclotron resonance, the Cherenkov resonance as well as through the anomalous cyclotron resonance, i.e. through the relation $\omega - kv_{\mathrm{beam},} = n\Omega_e$ where $n = 1, 0, -1$. Comparisons with growth rate calculations show excellent agreement with the experiment. Graduate student Xin An will present an invited talk on this work at the upcoming APS DPP meeting in Savannah, GA.

Fast-ion Campaign (W. Heidbrink, R. McWilliams (UC Irvine), B. Breizman (UT Austin), F. Jenko (MPI Garching/UCLA), S. Tripathi, S. Vincena, T. Carter (UCLA))

This campaign, led by Prof. W. Heidbrink (UCI), has been focused on the basic physics of the interaction between energetic ions and collective modes supported by a magnetized plasma. It is motivated in part by the need to understand the complex behavior of alpha particles in a burning, magnetically confined plasma. Work in this area has made use of lower current beams [11], allowing the study of test particle behavior, in addition to an up-to 25keV, 5A intense ion beam [12], allowing for the study of beam excitation of waves. Topics of research have included the classical transport of energetic ions in a magnetized plasma [13], Alfvén waves in a periodic mirror [14], Doppler-shifted cyclotron interaction of fast ions with shear Alfv'en waves [15, 16]

A recent campaign highlight is the investigation of the interaction between fast ions and drift-wave turbulence in LAPD. Confinement of fast ions is a critical issue in fusion experiments; reaching the burning plasma state and ignition requires confining alpha particles and allowing them to slow down and heat the fusion plasma. A key question is whether or not turbulence, which leads to significant degradation of confinement of thermal ions, can impact fast ion confinement. Many measurements of fast ion transport in tokamaks are consistent with classical collisional theory, with fast ion diffusion rates far below those for thermal ions (which are impacted by turbulence). However some recent measurements in tokamaks have indicated anomalously high diffusion of fast ions, in contradiction with earlier measurements and theoretical expectations. A widely accepted explanation for the low transport of fast ions is that energetic ions phase average over the microturbulence structure along its large gyro and drift orbits.

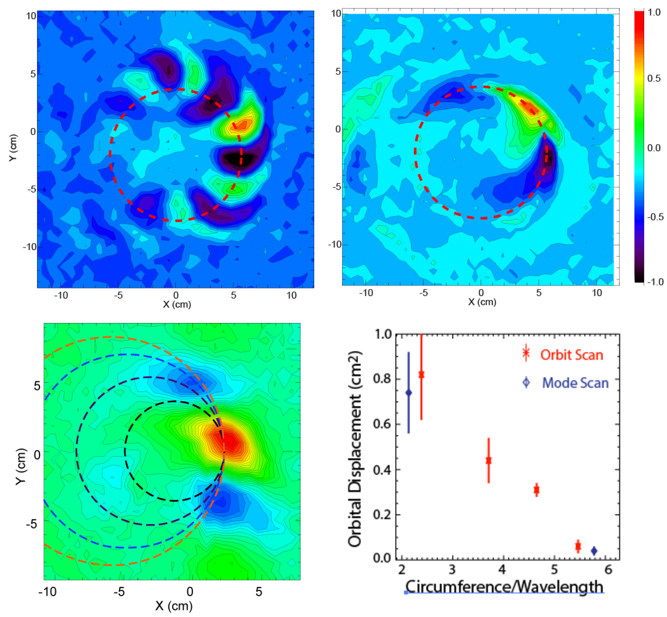

Figure 3:

An experiment performed in the LAPD illustrates this fundamental phase-averaging process [17–20]. A collimated, mono-energetic beam of high-energy ions is launched in a uniform solenoidal field. Obstacles are inserted into LAPD (either annular [18] or planar [21]) in order to produce pressure gradients that drive electrostatic fluctuations in the vicinity of the launched fast ion orbits. The ions traverse electrostatic fluctuations and their deflected trajectories are measured. The properties of the electrostatic fluctuations, in particular the wavenumber and correlation length, are varied through changing plasma properties, in particular magnetic field.

The response of the fast ions to the fluctuations is studied through varying the dimensionless parameter $k_\perp \rho_{\text{fast}}$, where $k_\perp$ is the typical perpendicular wavenumber of the fluctuations and ρ_{fast} is the gyroradius of the fast ions. In one version of the experiment (Fig. 3 (c)), the orbit size is varied while keeping the spatial scale of the fluctuations fixed ; in another version (Fig. 3 (a),(b)), the orbit size is held constant but the wave structure is varied. In both versions of the experiment, the orbital deflections are greatest when the mode structure and orbit size are comparable (Fig. 3 (d)). When the wave field oscillates rapidly in space, the ion phase-averages the potential fluctuations and is hardly deflected from its initial trajectory. This effort was coordinated with research on the DIII-D tokamak [22] and the toroidal basic plasma device TORPEX [20, 23] and was key to establishing that electrostatic fluctuations do not contribute substantially to the transport of fast ions in fusion devices [22].

Alfvén wave-wave interactions relevant to MHD turbulence (G. Howes, F. Skiff, C. Kletzing (U. Iowa); T. Carter, S. Dorfman (UCLA))

The unique capabilities of the Large Plasma Device (LAPD) have contributed to our successful study of the fundamental nonlinear interaction underlying astrophysical plasma turbulence, Alfven wave collisions. Early research on incompressible MHD turbulence in the 1960s [24, 25] emphasized the wave-like nature of turbulent motions in a magnetized plasma, suggesting that nonlinear interactions between counterpropagating Alfvén waves—or Alfvén wave collisions—mediate the turbulent cascade of energy from large to small scales. A major goal of the turbulence community was to demonstrate in the laboratory that this fundamental energy transfer mechanism, derived in the limit of incompressible MHD, persists under the realistic, weakly collisional plasma conditions relevant to many astrophysical environments. The LAPD provided nearly ideal experimental conditions for such an experiment, with sufficient size to launch Alfvén waves from opposite ends of the plasma chamber and unparalleled reproducibility to achieve a sufficient signal-to-noise ratio to measure definitively the resulting nonlinear transfer of energy to small scales.

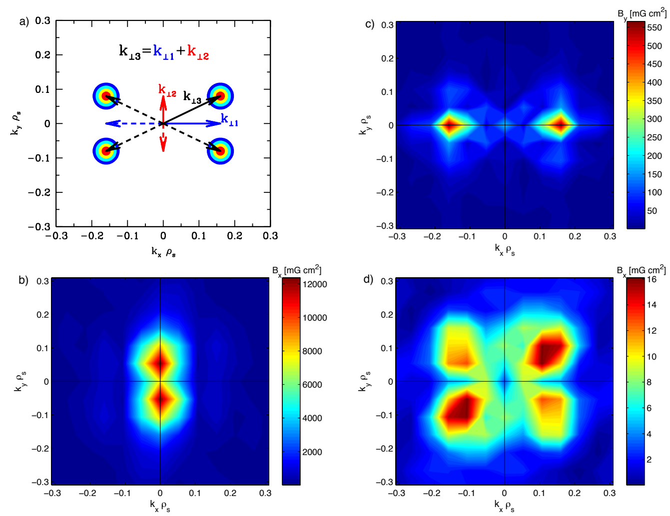

Figure 4: (a) Diagram of $\mathbf{k}_{\perp 1}$ for the ASW antenna (blue) and $\mathbf{k}_{\perp 2}$ for the Loop antenna (red). For the nonlinear daughter Alfvén wave, $\mathbf{k}_{\perp 3}$ (black) is the vector sum of the two antenna wave vectors, $\mathbf{k}_{\perp 3} = +\mathbf{k}_{\perp 1} \pm \mathbf{k}_{\perp 2}$ and $\mathbf{k}_{\perp 3} = -\mathbf{k}_{\perp 1} \pm \mathbf{k}_{\perp 2}$. Bullseyes indicate predicted power distribution of the nonlinear product. (b) Colormap (mG cm^2) of $\delta B_x(k_x,k_y)$ for the Loop antenna by itself. (c) Colormap of $\delta B_y(k_x,k_y)$ for the ASW antenna by itself. (d) Colormap of $\delta B_x(k_x,k_y)$ for the nonlinear daughter Alfvén wave.

This experiment was only possible through a collaboration that employed specialized equipment built by plasma experimentalists at the University of Iowa (UI) and UCLA and that followed an experimental design relying on theoretical work at UI. The experimental setup involved the launching of one Alfvén wave using UI's Arbitrary Spatial Waveform (ASW) antenna [26, 27] from one end of the LAPD chamber, and another Alfvén wave using UCLA's Loop antenna [28] from the other end. Theoretical calculations of the nonlinear energy transfer in the weakly nonlinear limit [29], along with validating gyrokinetic numerical simulations [30], guided a novel experimental design [31] that lead to the successful experimental verification of the physics of Alfvén wave collisions in the laboratory [32, 33], depicted in Figure 4. The theory predicts that the nonlinearly produced daughter Alfvén wave will contain power in Fourier space arising from all possible sums and differences of the Fourier power in the (b) Loop antenna wave and (c) ASW antenna wave, as shown by the four bullseye pattern shown in panel (a). The key experimental result (d) shows clearly this observational signature of the nonlinear daughter Alfvén wave. This result demonstrates that the experiment successfully measured, for the first time, the nonlinear interaction between counterpropagating Alfvén waves, the fundamental building block of astrophysical plasma turbulence.

Radiation Belt Remediation (Campaign) (Dennis Papadopoulos, Tom Antonsen (Univ. Maryland), Yuhou Wang, W. Gekelman, P. Pribyl, G. Morales (UCLA))

Laboratory observations of enhanced loss of magnetic mirror trapped fast electrons irradiated by a shear Alfvén Wave (SAW) are reported. A trapped energetic electron population (100keV) is generated in a magnetic mirror section (mirror ratio ≈ 2, length = 3.5 m) by an X-mode high power microwave pulse, and forms a hot electron ring due to the grad-B and curvature drift. SAWs of arbitrary polarization are launched externally by a Rotating Magnetic Field (RMF) source ($\delta B/B_o \approx 0.1\%$, $\lambda \approx 9$m). Irradiated by a right-handed circularly polarized SAW, the loss of electrons, in both the radial and the axial direction of the mirror field, is significantly enhanced and is modulated at $f_{\text{Alfvén}}$. The periodical loss continues even after the termination of the SAW. Experimental observations suggest that a spatial distortion of the ring is formed in the SAW field and creates a collective mode of the hot electron population that degrades its confinement and leads to electron loss from the magnetic mirror.

The hot electron ring was produced using a magnetron ($f = 2.45$ GHz) coupled to the plasma with a circular waveguide. The microwaves were resonant with electrons at the second cyclotron harmonic (400G near the center of the magnetic mirror). A shear Alfvén wave launched with a rotating magnetic field antenna (located outside of the mirror) de-trapped all electrons in a wide energy range (100 eV < E<3 MeV). Evidence of SAW effectively de-trapping the hot electron population is found in the x-ray flux measurement when the trapped electrons are further accelerated to energies that enable hard x-ray production [34]. Shown in Fig. 5 are traces E-J, showing that a burst of x-rays generated by hot electrons escaping the mirror trap and striking metallic surfaces appears during the Alfvén wave propagation time. A large flux of x-ray appears while the Alfvén wave is first turned on. After this initial burst, the x-ray flux decreases as the remaining hot electron population is depleted during the rest of the Alfvén on time. After the Alfvén wave is turned off, the x-ray flux slowly builds up due to the presence of ECRH which remains on until $t = 30$ ms.

After the ECRH terminates at $t = 30$ ms, a population of fast electrons persists in the mirror, and can be de-trapped by launching Alfvén waves at these late times, as evidenced by x-ray bursts in Fig. 5 traces K-T. The estimated trapping time for a 200 keV electron is 40 ms before its loss from cumulative collisions with the helium atoms and ions. The decay of the x-ray burst intensity after $t = 31$ ms reflects the decay of the number of x-ray producing hot electrons still in the mirror. This measurement proves that the electron loss due to the shear Alfvén wave is not related to the presence of the microwaves. An X ray tomography system was developed to establish here the hot electrons go after having interacted with the wave [35]. Most of the fast electrons strike the waveguide, which is very close to the plasma edge. Electrons are also lost of a mesh anode at the end of the device. These have been scattered out of the loss cone [36].

Local group research

From heat transport in LAPD to chaotic fluctuations in DIII-D (J. Maggs, G. Morales)

An unexpected research path has lead to a connection between basic heat transport experiments in LAPD to the identification that the density fluctuations in the L-mode plasmas in the DIII-D tokamak are chaotic. To simplify the study of electron heat transport, a series of basic experiments have been performed in LAPD. The generic experiment uses a small (3mm diameter), single-crystal LaB_6 cathode

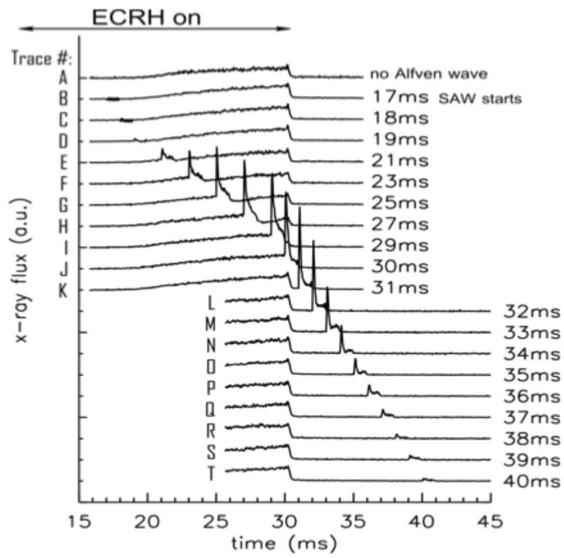

Figure 5: Time series of x-ray flux measured by an un-collimated detector, designated by letters A-T. The ECRH is on from t=0 to 30 ms, but only after about 20 ms are there sufficient high energy electrons to produce a measurable x-ray flux. Trace A is measured without launching the SAW. In traces B-T a 100 cycle shear Alfvén wave pulse (total duration = 0.87 ms), starting at different times labeled on the graph is launched. Each trace is averaged over 50 plasma shots.

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 ($\sim$8 m), narrow ($\sim$5mm 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. To elucidate the dynamics leading to anomalous transport the permutation entropy analysis (C-H plane technique) developed by [37] is applied to the probe signals. This technique is an effective method to identify the various possible dynamical processes (coherent, stochastic, chaotic, fractional Brownian motion). In a characteristic C-H display, the vertical axis corresponds to the Jensen-Shannon complexity, C, and the horizontal axis to the normalized Shannon entropy, H. These quantities are obtained from the Bandt-Pompe probability distribution [38] generated from the time series. Through these techniques it has been conclusively shown that the LAPD anomalous heat transport is a consequence of chaotic dynamics [39–42]. Motivated by this finding a collaboration was established with Dr. T. Rhodes who performs very delicate Doppler-backscattering (DBS) measurements of the fluctuations in the DIII-D tokamak. The analysis methodology developed for the LAPD was applied to the DIII-D and it was found that the behavior of the fluctuations in that seemingly different experiment exhibit the same chaotic behavior as the simple LAPD experiment [43].

Ion-ion hybrid Alfvén wave resonator (S. Vincena, G. Morales, J. Maggs)

A detailed experimental and theoretical investigation has firmly established the reality of a wave resonator based on the concept of wave reflection along the confinement magnetic field at a spatial location where the wave frequency matches the local value of the ion-ion hybrid frequency [44–48].

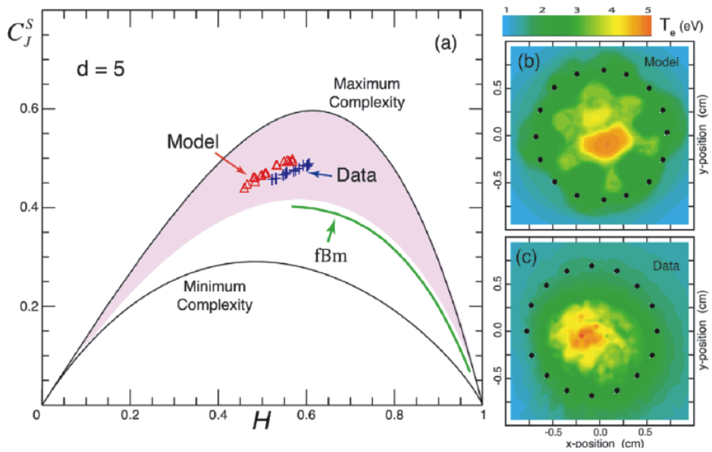

Figure 6: C-H plane analysis of data in LAPD experiment and of prediction of a chaotic advection model shows LAPD dynamics are chaotic.

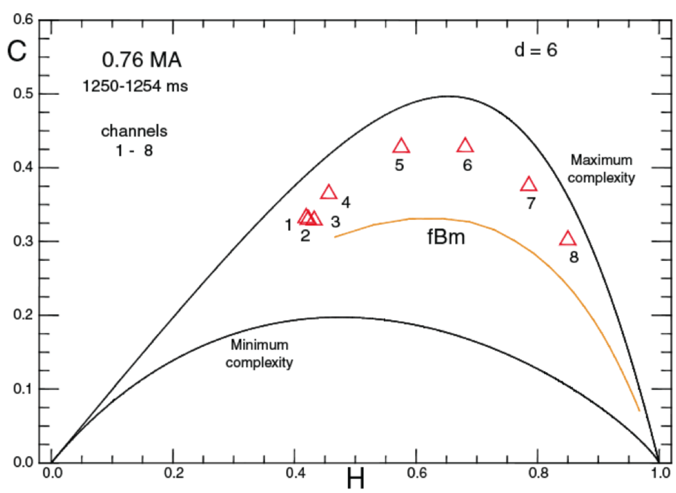

Figure 7: C-H plane analysis of Doppler-backscattering (DBS) from DIII-D shows that the signals from all the channels (different radii) are in the chaotic region, as in the LAPD experiment.

Such a situation can be realized by shear Alfvén waves in a magnetized plasma with two ion species because this mode has zero parallel group velocity and experiences a cut-off at the ion-ion hybrid frequency. Since the ion-ion hybrid frequency is proportional to the magnetic field, in the presence of a magnetic well a wave resonator can be formed. This is a structure that arises naturally in planetary magnetospheres, and has relevance to mirror and tokamak fusion devices because they must operate with a D-T mix, and their confinement fields have axial gradients. A series of experiments were performed in LAPD which started with the basic measurement of the properties of shear Alfvén waves in the presence of two ion species in a uniform plasma. Then it was established that the waves experience a cut-off when propagating into a magnetic ramp, and finally a plasma with a magnetic well in the center region of LAPD was explored. This led to the conclusive identification of resonator behavior in a laboratory environment when an external current loop excited trapped modes, both in a pulsed and continuous operation.

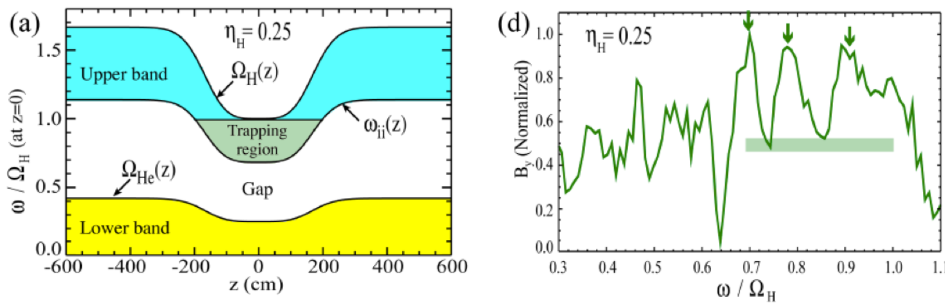

Figure 8: Left: Axial variation of resonator in LAPD for a H-He^{+} plasma showing propagation bands and gap. Right: Spectrum of magnetic fluctuations inside resonator shows resonator peaks; arrows are theoretically-predicted frequencies of trapped modes.

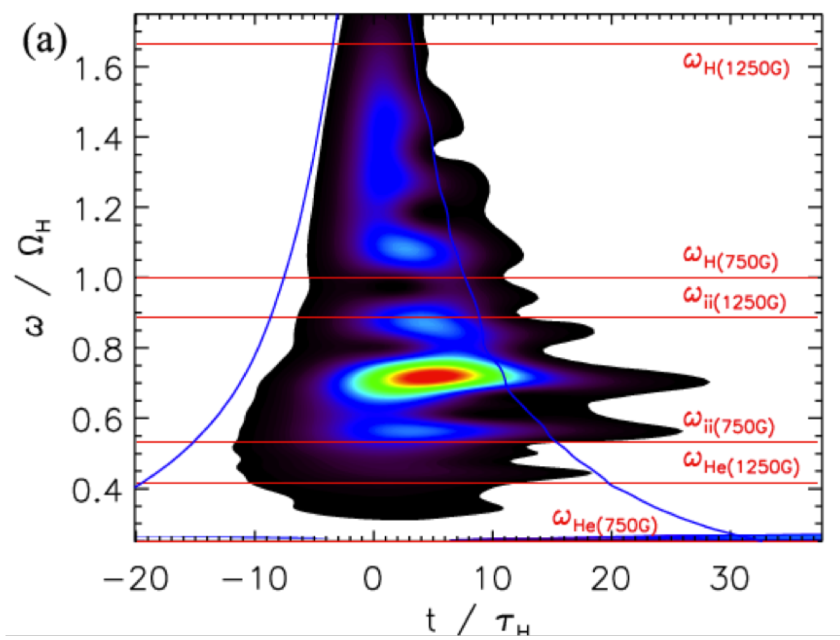

Figure 9: Contours of Morlet wavelet amplitude of magnetic field fluctuations show the response of the H^{+}-He^{+} resonator after excitation with a current impulse of width $\Delta t = \tau_H$ at $t = 0$. Red spot shows a large response and long lifetime of a trapped mode.

This work lead to a Ph.D. dissertation by W. Farmer and has been reported in seven publications. The most recent effort has used the insight from the LAPD studies to assess the properties of such a resonator for the expected ITER environment and its excitation by energetic alpha particles [49].

Magnetic Flux Ropes (W. Gekelman, B. Van Compernolle; E. Lawrence, T. DeHaas, D. Hong (Graduate Students))

The UCLA group (W. Gekelman, B. Van Compernolle, and graduate students past (Eric Lawrence) and present (Tim DeHaas, Dooran Hong) have done groundbreaking work on the interaction of magnetic flux ropes. We are presently collaborating with W. Daughton (LANL) on a experiment dedicated to the memory of Tom Intrator.

The first ever experimental determination [50] of a quasi-seperatrix layer (QSL) was made on the LAPD in 2009. A QSL is a 3D region in which magnetic field lines that start close to one another diverge rapidly in space. The value of Q is a measure of the divergence. If two field lines pass through a reconnection region, one or more components of B can rapidly change within it leading to a large value of Q. This is illustrated in Figure 10.

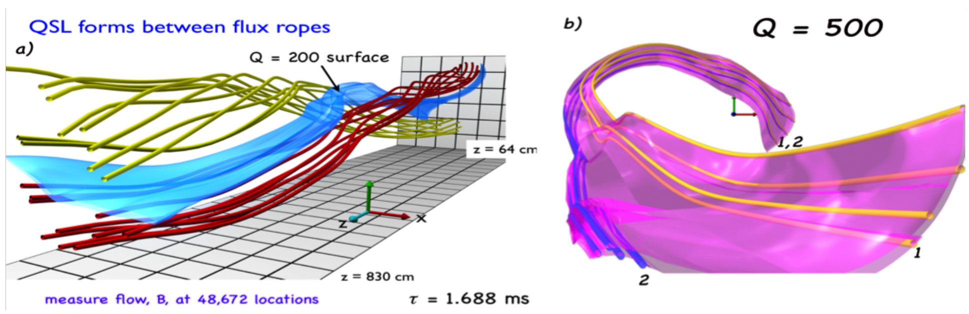

Figure 10: (a) The "blue" surface is a QSL (Q=100) which is located between two flux ropes which are colored red and yellow. The flux ropes are calculated by following field lines through the dense grid of measurement points. (b) A Q=500 surface with several field lines within it. One set of field lines labeled (1,2) are initially 0.5 mm apart but are 12.5 cm apart when they reach the end of the measurement volume 8.3 meters away.

QSLs have been observed in the collision of two or more flux ropes [51, 52]. In a separate tearing mode experiment QSL's were discovered when 3D current systems expanded in space and no field line reconnection was involved. For the first time the total electric field was measured using a combination of magnetic and emissive probes. The parallel resistivity, η was derived from the data and can be 100's of times the Spitzer resistivity in small regions of space during the collision of flux ropes. The resistivity was localized to the gradients in the current of the flux ropes and also within the QSL. Figure 11 shows the QSL, current and η evaluated from the measured plasma current and electric field.

It is clear that there is more than one process at work. The three dimensional case is very different from the traditional 2D models which cannot predict the reconnection rate we measured by integrating the electric field along magnetic field lines.

We have also studied chaos associated with the ropes and found that it peaks when the flux ropes exist along with shear Alfvén waves [53]. When the BaO cathode is replaced with a LaB_6 cathode

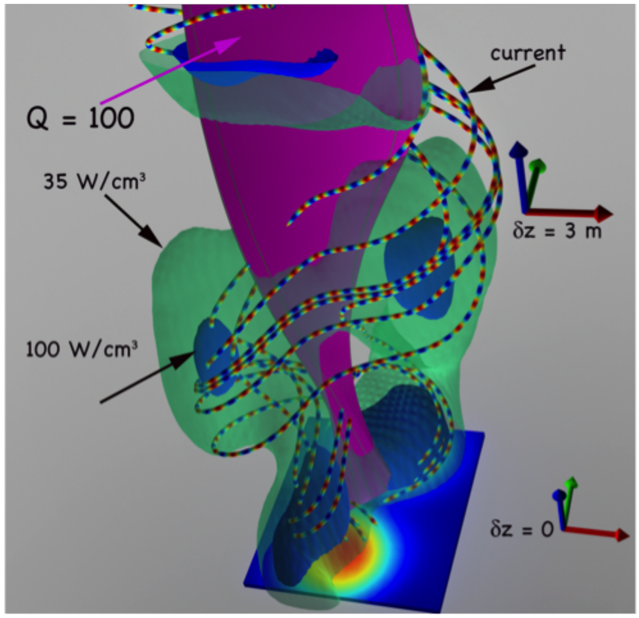

Figure 11: Bottom is the plasma current in a plane 64 cm from the origin of the ropes. The current of one rope is clearly visible and the current density in the center is 5A/cm^2. A QSL of 100 is shown along with several current field lines colored in stripes. Two isosurfaces of the heating power are shown. Heating is observed within the QSL at locations where reconnection occurs but significant heating also occurs within the flux tubes.

we will be able to do these experiments are relatively high plasma beta and Lundquist number ($10^5 < L < 10^6$). How do intense Alfvén waves interact with flux ropes (which can also be thought of as Alfvén waves)? What is the mechanism for this interaction and can it lead to magnetic turbulence? The LAPD is the only machine in which these experiments can be performed.

Turbulence, transport and flows in LAPD (T. Carter, J. Maggs, P. Popovich (UCLA) M. Umansky (LLNL), B. Dudson (U. York); D. Schaffner, B. Friedman, G. Rossi (grad students))

Suppression of turbulent transport by sheared flow has been documented in a range of experiments and simulations [54]. However we still lack a complete, quantitatively correct theoretical model of transport suppression by sheared flow. This theoretical understanding is essential in the development of a predictive capability for turbulent transport, a capability that is critical in ensuring the success of future experiments such as ITER. Experiments performed on LAPD have documented in detail the response of turbulence and turbulent transport to externally-controlled flow and flow shear.

Azimuthal flow is driven in LAPD through biasing either the vacuum chamber wall or an annular limiter relative to the plasma source cathode. Cross-field currents are driven (carried by ions due to Pedersen conductivity), leading to $\mathbf{j} \times \mathbf{B}$ torque and azimuthal rotation. In the case of biasing the vacuum chamber wall, H-mode-like behavior is observed, with suppression of turbulent particle transport and steepening of the edge density profile [55, 56]. Transport is reduced from Bohm-like levels to classical if the wall bias is above a threshold value (a factor of 100 reduction in particle diffusion coefficient) [55].

A more detailed examination of the impact of flow shear on turbulent transport was enabled through the introduction of an annular limiter which brings a biasable surface closer to the plasma edge. Biasing the limiter relative to the cathode provides the ability to vary the edge flow and flow shear continuously. As the LAPD plasma spontaneously rotates in the ion diamagnetic direction and biasing tends to drive flow in the electron diamagnetic direction, zero shear and zero flow states are accessible as well as flow reversal. Figure 12 shows the measured density gradient scale length and turbulent particle flux as the flow shear is varied continuously in the edge of LAPD. The density gradient steepens (L_n decreases) as shear is increased, indicating a reduction in cross-field transport. Consistent with this, the measured turbulent particle flux drops monotonically with increasing shear [57]. The shearing rate on the x-axis is normalized to the turbulent autocorrlelation time, as measured with zero flow shear; this is taken as a proxy for the eddy decorrelation (or "turn-over") time. Substantial changes in both L_n and particle flux occur for normalized shearing rates of order unity.

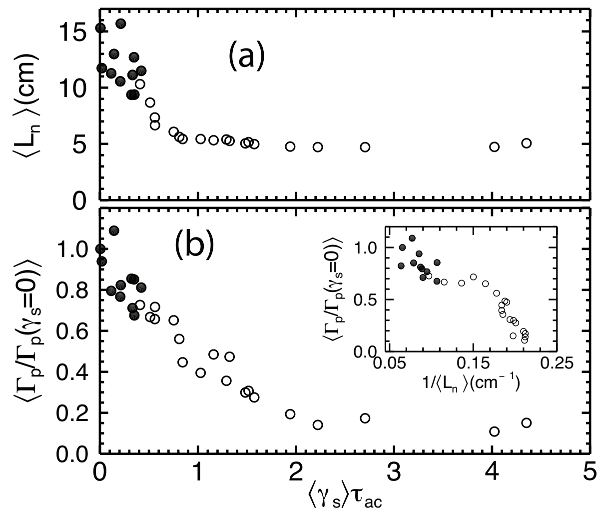

Figure 12: (a)Gradient scale length versus shearing rate. (b)Particle flux normalized to no-shear flux as a function of normalized shearing rate. Filled symbols represent points with flow in the ion diamagnetic direction. Inset: Measured turbulent particle flux versus gradient scale length.

LAPD experimental data has been compared to a number of analytical theoretical models of shear suppression [58]. The ability to continuously vary the edge flow shear in LAPD allowed the collection of data for both the weak ($\gamma_s\tau_{ac}$ 1) and strong ($\gamma_s\tau_{ac}$ 1) shearing regimes. The data was fit to two functional forms motivated by theoretical models developed for these two regimes. While these functional forms do fit the data reasonably well, the fit coefficients obtained are not a good match to theoretical predictions, suggesting that new models may be needed to explain LAPD data. Future work will focus on comparison of LAPD data to numerical simulation (e.g. using the GENE code) and to more recently developed analytical models of shear suppression of turbulent transport [59].

Turbulence in magnetically confined plasmas is often attributed to linear instabilities, which can grow from infinitesimal initial perturbations (e.g. thermal noise). However, it is well known in the hydrodynamics community that linear instability (normal mode) analysis fails at predicting turbulent onset for a number of physical situations, for example water flow in cylindrical pipes (Poiseuille flow). In these cases, turbulence arises even though all linear modes are stable, meaning infinitesimal perturbations on the laminar state cannot grow exponentially. Nevertheless, finite amplitude perturbations can still excite turbulence. We have found that the same can be true in pressure-gradient-driven turbulence in LAPD. Simulations of LAPD turbulence have been performed using the BOUT++ code, which has been modified for LAPD geometry and boundary conditions [60–63]. Even though the resistive drift-Alfvén wave is linearly unstable, the simulations reveal that a nonlinear instability controls the saturated turbulent state [64–67], as shown in Figure 13(a). Consistent with this observation, transient growth of linearly-stable flute-like ($k = 0$) modes is observed, as shown in Figure 13(b).

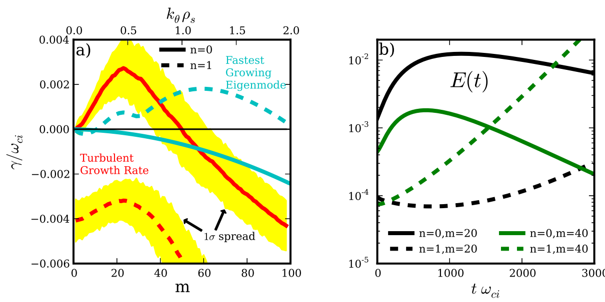

Figure 13: (a) Linear evolution of energy starting from a turbu- lent initial state. The $n = 0$ curves have an initial period of transient growth before exponentially decaying. b) Lin- ear and turbulent growth rate spectra for $n = 0$ (solid lines) and $n = 1$ (dashed lines) Fourier components. The linear growth rates are those of the least stable eigenmodes, while the turbulent growth rates represent the time rate of change of the mode energy divided by twice the mode energy from the linear simulation. The shaded region marks the 1σ spread in the turbulent spectrum, obtained from the distribution of growth rates in the nonlinear simulation.

A similar conclusion was previously reached by authors examining tokamak edge turbulence simulations [68–70]. The dominance of a nonlinear instability makes prediction of turbulence and turbulent transport in magnetic confinement experiments difficult as linear instability calculations, which are relied on quite heavily in the fusion community, can be misleading. Using input from analysis of BOUT++ simulations, a technique has been developed that enables the prediction of the nonlinear properties of a turbulent system using simple linear, but “nonmodal”, calculations. The technique successfully predicts the structure of the nonlinearly saturated state in LAPD turbulence simulations and provide a linear technique to estimate turbulent saturated amplitude and particle transport [66, 67].

This work has resulted in two graduate students completing PhDs over the last 5 year period (David Schaffner and Brett Friedman) and the training of two postdoctoral fellows (Pavel Popovich and Brett Friedman).

Facility Development

Since its inception, the BaPSF has continually improved the capabilities and diagnostics of the LAPD device. In the next funding period, among other improvements, we propose one major upgrade to the LAPD. This upgrade will replace the primary plasma source, currently a large-area Barium Oxide emissive cathode, with a Lanthanum Hexaboride (LaB6) based cathode. Large area LaB6 cathodes have been developed over the last funding period by the UCLA group (see the appendix for more details) and offer many advantages to BaO cathodes, including access to important new parameter regimes and operational advantages.

LaB_6 cathodes offer far more emission current density, and therefore higher density and temperature plasmas, than BaO cathodes. Recently, a 20cm LaB_6 cathode has been installed on LAPD (see appendix), allowing for the production of high density and temperature "core" plasmas within the larger BaO-produced plasma. Plasmas are produced with significantly higher density (up a factor of 50 from BaO to 5×10^{13} cm^{-3}) and higher electron temperature (up to $12 - 15$eV from ~ 5 eV with BaO). At this electron density and temperature, the ion-electron collisional energy exchange time is calculated to be ~ 0.2 ms and, consistent with this, an increased ion temperature is observed in the new LaB_6 produced plasma. Initial measurements of shape of the He II 468.6 nm ion emission line have been performed using a 2m monochrometer. These measurements have been compared to PrismSPECT Spectral Analysis Code calculations yielding a best-fit temperature of $T_i \sim 6$ eV, a significant enhancement over the BaO produced plasma ion temperature of $T_i \lesssim 1$ eV. The achievement of a factor of 100x increase in plasma pressure along with warm ions allows:

- Achievement of high-beta, magnetized plasmas (turbulence and transport at high beta, wave physics at high beta, instabilities (mirror and firehose)
- Study of kinetic ion physics (Landau, Barnes and Cyclotron damping)
- Studies in a regime with similar density to tokamak boundary plasmas (turbulence, RF, etc)

Operationally, Lab_6 cathodes are far more robust than BaO cathodes. BaO cathodes are sensitive to Oxygen; any significant exposure to Oxygen will "poison" the cathode, substantially lowering its emission current. For this reason, any unintentional vacuum leak leads to an extended shutdown: it takes around 10 days to replace a poisoned cathode (cathode must be removed, cleaned, re-coated and slowly "converted" while heated under vacuum before it is ready to be operated). In addition, the introduction of apparatus into the vacuum chamber in order to perform experiments (e.g. probes or antennas) must be done very carefully. New apparatus is pumped down to 5×10^{-6} Torr prior to being opened and inserted into the vacuum chamber to prevent Oxygen from being introduced. For typical probes it can take 2 hours to achieve this level of vacuum and it can take up to a day of pumping for larger items (e.g. antennas, ion beams). The efficiency of gathering data using LAPD is therefore reduced by time waiting to open new probes (e.g. after moving a probe to a new axial location). LaB6 cathodes are far more robust and do not suffer from the same sensitivity to vacuum incidents. With a LaB_6 primary cathode we anticipate that pumping probes into the 10^{-4} Torr range will be sufficient before opening (this typically takes 10-15 minutes). Using LaB6 for the primary LAPD cathode will therefore significantly increase efficiency of data taking during the typical run week. Overall uptime for the LAPD has been very good over the past 5 year period, but would be significantly better with a LaB_6 plasma source: for example, a prototype LaB_6 plasma source was operated at 1 Hz continuously for 1 year in the ETPD without need for a maintenance opening.

Proposed Research - Local Group

Research on Three Dimensional Current Systems and Magnetic Field Line Reconnection (W. Gekelman, B. Van Compernolle)

The UCLA group (W. Gekelman, B. Van Compernolle, graduate students and external users: W. Daughton (LANL), will continue their successful program on 3D reconnection. Much of the past work has centered on reconnection in systems of magnetic flux ropes. The first ever experimental determination [50] of a quasi-seperatrix layer (QSL) was made on the LAPD in 2009. A QSL is a 3D region in which magnetic field lines that start close to one another diverge rapidly in space. The value of Q is a measure of the divergence. If two field lines pass through a reconnection region, one or more components of B can rapidly change within it leading to a large value of Q. This has been seen in the collision of two or more flux ropes [51]. In a separate tearing mode experiment QSL's were discovered when 3D current systems expanded in space and no field line reconnection was involved. For the first time the total electric field was measured using a combination of magnetic and emissive probes. The parallel resistivity was derived from the data and can be 100's of times the Spitzer resistivity in small regions of space during the collision of flux ropes. The resistivity was localized to the gradients in the current of the flux ropes and also within the QSL. It is clear that there is more than one process at work. The three dimensional case is very different from the traditional 2D models which cannot predict the reconnection rate we measured by integrating the electric field along magnetic field lines. We have also studied chaos associated with the ropes and found that it peaks when the flux ropes exist along with shear Alfvén waves [53].

We will continue to explore the nature of 3D current systems and reconnection in future experiments. What are all the instabilities that give rise to large plasma resistivity's. Are high frequency waves involved? With the planned replacement of the BaO cathode we will be able to do these experiments are relatively high plasma beta and Lundquist number ($10^5 < L < 10^6$). How do intense Alfvén waves interact with flux ropes (which can also be thought of as Alfvén waves)? What is the mechanism for this interaction and can it lead to magnetic turbulence? The LAPD is the only machine in which these experiments can be done. We look forward to continued collaboration with the Los Alamos group as well with others interested in this topic.

Avalanche phenomena in magnetized plasmas (B. Van Compernolle, G. Morales)

Avalanches are sudden events that cause major changes over an extended region of a physical system. The origin of avalanches is the presence of a steep gradient in one of the system parameters. Often there is a threshold value for the gradient; when it is exceeded, a complex sequence of processes is triggered whose role is to relax the gradient below the threshold value. In several environments, such as an externally-heated or fueled plasma, the sources reestablish the gradient and further cause it to exceed the threshold value. A sequence of avalanches can then occur, but the actual time of appearance of an individual event displays a marked degree of unpredictability. The behavior is intermittent and causes the parameters of the system to evolve from place to place, i.e., there is an associated "transport" that occurs. It is this type of intermittent avalanche phenomena that will form the central theme of the proposed studies.

The project will focus on avalanches triggered by gradients in plasma temperature and density across the magnetic field. This is a situation encountered in natural plasmas (e.g., sun, earth's magnetotail) and in fusion devices. The technological breakthrough that makes possible the implementation of an ideal basic configuration for studies of avalanches in magnetized plasmas is a reliable and flexible LaB_6 cathode source that has been developed in BaPSF.

Preliminary results demonstrating the controlled generation of avalanches using a ring-shaped heat source have been recently published [71]. In the near future a full characterization of cross-field avalanches will be made using the diagnostic tools available at the LAPD laboratory. Detailed spatial and temporal measurements of density, temperature, plasma potential, flows (both ExB and diamagnetic), and magnetic fields, will be undertaken for a wide range of parameter values, including: heating power, strength of confinement magnetic field, neutral gas fill-pressure and ionic species.. The steepness of the pressure gradient can be adjusted by changing the heating power, which determines the peak electron temperature within the hot ring. Although the preliminary results were performed with a constant bias voltage applied to the LaB_6 source, a straightforward extension is to control, and change, the bias voltage during the experiment. This capability permits the identification of various features, such as hysteresis and response to modulations of the critical gradient.

In summary, the wide range of experimental capabilities at BaPSF allows for the investigation of a number of important questions related to avalanches in magnetized plasmas including

quantitative information about SOC dynamics, the formation and evolution of streamers, the effects of flows, the connection between avalanches and 'blobs', and the role of nonlocal transport of both temperature and density during avalanche events.

Turbulence and Transport (T. Carter, S. Vincena)

Turbulence and Transport in increased β, warm ion plasmas

We propose to study the fundamental physics of pressure-gradient-driven instabilities and associated turbulence and transport in an experiment where the β value can be varied over several orders of magnitude, from $\beta \sim 10^{-4}$ to $\beta \sim 1$. In the near term, this work is enabled by the new secondary small LaB6 plasma source; the new larger area LaB_6 plasma source that can create plasmas with significantly increased thermal energy density, which, along with the ability to vary the magnetic field while keeping the plasma magnetized, allows

for accessing a wide range of β values. In addition, the production of warm ions provides an opportunity to investigate ion kinetic effects on the turbulence. In the proposed work, focus will

be given to a detailed, quantitative study of the response of turbulence, turbulent transport, and spontaneously generated flows to variation of β. Existing capabilities to externally control flow and flow shear will be used to extend previous work on the suppression of particle transport by flow shear to higher β regimes. Finally, we will undertake work to make a very important further development regarding the capability to simulate LAPD plasmas, including kinetic effects. The state-of-the-art gyrokinetic turbulence code GENE, capable of handling high β electromagnetic effects, will be used for simulation studies of LAPD plasmas. These will be the first global ab initio computations of LAPD plasmas, allowing to carry out simulation-experiment comparisons in the high β regime with unprecedented quality.

Turbulence and transport in multiple ion species plasmas

Physics of Compressional Alfven waves in LAPD (Vincena, Tripathi, Van Compernolle, Carter)

[To be added]

Future Campaign Development

The topical campaign has been an extremely successful operating mode and will continue to be emphasized in the next funding cycle. The development of new campaigns will proceed in consultation with the BaPSF council and through interaction with members of the research community. Support is requested to run workshops at UCLA (roughly every other year) to support the development and operation of campaigns. Here are presented several possible research topics that could be the subject of future campaigns; actual

a). *"Solar Wind" Campaign.* Alfvénic turbulence is observed directly in the solar wind, indirectly in the interstellar medium and is thought to play an important role in momentum transport and heating in accretion disks; a campaign in this area could have a major impact. Such a campaign would build on existing efforts, including initial Alfvén single wave-wave interaction studies on LAPD47 and detailed comparisons between astrophysical turbulence simulation codes and LAPD data48. Possible near term activities in such a campaign could include extension of Alfvén wave studies to high beta in LAPD using a LaB6 plasma source and studies of high-beta anisotropy driven instabilities such as the mirror or firehose instability, both thought to be very important in establishing the turbulent spectrum and heating in turbulence at high beta. Greg Howes (U. Iowa) has agreed to help lead this campaign. [More to be added]

b). *RF Physics Campaign.* A campaign proposal that has already been under development is the study of the basic physics of radiofrequency (RF) waves for heating and current drive. R. Perkins (PPPL) has expressed interest in coordinating a campaign on fast wave physics, in particular focused on interaction with edge plasmas and the generation of RF sheaths. Initial research focus would be placed on RF sheaths driven by fast wave antennas in an attempt to understand RF sheaths and validate models used in fusion RF codes. Impurity production associated with RF-sheath-driven sputtering is a key issue for ITER [45].

[Add more here, discussing Helicon current drive physics and potential involvement from GA (Pinsker)]

Intellectual Merit.

The BaPSF allows the detailed study, under controlled conditions, of fundamental questions in plasma science that cannot be addressed in any other laboratory. The results obtained impact a wide range of frontier topics in fusion and space plasma research. It also lays the foundation for future developments in plasma technology. Through creative developments of plasma sources and the operation of complementary plasma devices exploited thorough focused campaigns, the operation of BaPSF constitutes a transformative concept within plasma science.

Broader Impacts.

One of the broader impacts of the BaPSF is that it provides unique opportunities in the training of young researchers from both large and small institutions. Graduate students, postdoctoral researchers and assistant professors have access to cutting edge research devices without the burden of maintenance. The ideal mid-scale size of the devices allows for individual creativity to blossom within a team research environment that mixes young students with distinguished senior researchers. BaPSF fosters and engenders collaborations between domestic and international institutions and scientists from diverse

areas, such as fusion, space and industrial applications. The topical campaigns made possible by BaPSF provides a forum for the interaction of experimentalists, theoreticians and modelers from varied backgrounds, promoting the cross-fertilization of ideas and techniques. Research at BaPSF is published over a wide range of refereed journals and is presented extensively at prestigious national and international conferences covering all aspects of plasma science. The LAPTAG program run by the facility also provides research opportunities for high school students and teachers.

References

[1] http://plasmalab.pbworks.com.

[2] D.B. Schaeffer, Everson E.T., Bondarenko A.S., S.E. Clark, C.G. Constantin, S. Vincena, B. Van Compernolle, S.K.P. Tripathi, D. Winkse, W. Gekelman, and C. Niemann. Laser-driven, magnetized quasi-perpendicular collisionless shocks on the Large Plasma Device. *Phys. Plasmas*, 21:056312, 2014.

[3] C. Niemann, W. Gekelman, C. G. Constantin, E. T. Everson, D. B. Schaeffer, A. S. Bondarenko, S. E. Clark, D. Winske, S. Vincena, B. Van Compernolle, and P. Pribyl. Observation of collisionless shocks in a large current-free laboratory plasma. *Geophysical Research Letters*, 41(21):7413–7418, 2014.

[4] S. E. Clark, E. T. Everson, D. B. Schaeffer, A. S. Bondarenko, C. G. Constantin, C. Niemann, and D. Winske. Enhanced collisionless shock formation in a magnetized plasma containing a density gradient. *Phys. Rev. E*, 90:041101, Oct 2014.

[5] R.M. Thorne. Radiation belt dynamics: The importance of wave-particle interactions. *Geophysical Research Letters*, 37(22):L22107, 2010.

[6] G. D. Reeves, H. E. Spence, M. G. Henderson, S. K. Morley, R. H. W. Friedel, H. O. Funsten, D. N. Baker, S. G. Kanekal, J. B. Blake, J. F. Fennell, S. G. Claudepierre, R. M. Thorne, D. L. Turner, C. A. Kletzing, W. S. Kurth, B. A. Larsen, and J. T. Niehof. Electron acceleration in the heart of the van allen radiation belts. *Science*, 341(6149):991–994, 2013.

[7] Richard B. Horne, Richard M. Thorne, Sarah A. Glauert, Jay M. Albert, Nigel P. Meredith, and Roger R. Anderson. Timescale for radiation belt electron acceleration by whistler mode chorus waves. *Journal of Geophysical Research: Space Physics*, 110(A3):A03225, 2005.

[8] R. M. Thorne, W. Li, B. Ni, Q. Ma, J. Bortnik, L. Chen, D. N. Baker, H. E. Spence, G. D. Reeves, M. G. Henderson, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, J. B. Blake, J. F. Fennell, S. G. Claudepierre, and S. G. Kanekal. Rapid local acceleration of relativistic radiation-belt electrons by magnetospheric chorus. *Nature*, 504(7480):411–414, 12 2013.

[9] B. Van Compernolle, J. Bortnik, P. Pribyl, W. Gekelman, M. Nakamoto, X. Tao, and R. M. Thorne. Direct detection of resonant electron pitch angle scattering by whistler waves in a laboratory plasma. *Phys. Rev. Lett.*, 112:145006, Apr 2014.

[10] B. Van Compernolle, X. An, J. Bortnik, R. M. Thorne, P. Pribyl, and W. Gekelman. Excitation of chirping whistler waves in a laboratory plasma. *Phys. Rev. Lett.*, 114:245002, Jun 2015.

[11] Y. Zhang, H. Boehmer, W. W. Heidbrink, R. McWilliams, D. Leneman, and S. Vincena. Lithium ion sources for investigations of fast ion transport in magnetized plasmas. *Review of Scientific Instruments*, 78(1):–, 2007.

[12] S. K. P. Tripathi, P. Pribyl, and W. Gekelman. Development of a radio-frequency ion beam source for fast-ion studies on the large plasma device. *Review of Scientific Instruments*, 82(9):–, 2011.

[13] L. Zhao, W. W. Heidbrink, H. Boehmer, R. McWilliams, D. Leneman, and S. Vincena. Measurements of classical transport of fast ions. *Physics of Plasmas*, 12(5):–, 2005.

[14] Yang Zhang, W. W. Heidbrink, H. Boehmer, R. McWilliams, Guangye Chen, B. N. Breizman, S. Vincena, T. Carter, D. Leneman, W. Gekelman, P. Pribyl, and B. Brugman. Spectral gap of shear alfvén waves in a periodic array of magnetic mirrors. *Physics of Plasmas*, 15(1):–, 2008.

[15] Yang Zhang, W. W. Heidbrink, H. Boehmer, R. McWilliams, S. Vincena, T. A. Carter, W. Gekelman, D. Leneman, and P. Pribyl. Observation of fast-ion doppler-shifted cyclotron resonance with shear alfvén waves. *Physics of Plasmas*, 15(10):–, 2008.

[16] Yang Zhang, W. W. Heidbrink, Shu Zhou, H. Boehmer, R. McWilliams, T. A. Carter, S. Vincena, and M. K. Lilley. Doppler-shifted cyclotron resonance of fast ions with circularly polarized shear alfvén waves). *Physics of Plasmas*, 16(5):–, 2009.

[17] Shu Zhou, W. W. Heidbrink, H. Boehmer, R. McWilliams, T. Carter, S. Vincena, S. K. P. Tripathi, P. Popovich, B. Friedman, and F. Jenko. Turbulent transport of fast ions in the large plasma device. *Physics of Plasmas*, 17(9):–, 2010.

[18] S. Zhou, W. W. Heidbrink, H. Boehmer, R. McWilliams, T. A. Carter, S. Vincena, B. Friedman, and D. Schaffner. Sheared-flow induced confinement transition in a linear magnetized plasma. *Physics of Plasmas*, 19(1):–, 2012.

[19] Shu Zhou, W. W. Heidbrink, H. Boehmer, R. McWilliams, T. A. Carter, S. Vincena, S. K. P. Tripathi, and B. Van Compernolle. Thermal plasma and fast ion transport in electrostatic turbulence in the large plasma devicea). *Physics of Plasmas*, 19(5):–, 2012.

[20] W W Heidbrink, H Boehmer, R McWilliams, A Preiwisch, Y Zhang, L Zhao, S Zhou, A Bovet, A Fasoli, I Furno, K Gustafson, P Ricci, T Carter, D Leneman, S K P Tripathi, and S Vincena. Measurements of interactions between waves and energetic ions in basic plasma experiments. *Plasma Physics and Controlled Fusion*, 54(12):124007, 2012.

[21] T. A. Carter. Intermittent turbulence and turbulent structures in a linear magnetized plasma. *Phys. Plasmas*, 13:010701, 2006.

[22] D. C. Pace, M. E. Austin, E. M. Bass, R. V. Budny, W. W. Heidbrink, J. C. Hillesheim, C. T. Holcomb, M. Gorelenkova, B. A. Grierson, D. C. McCune, G. R. McKee, C. M. Muscatello, J. M. Park, C. C. Petty, T. L. Rhodes, G. M. Staebler, T. Suzuki, M. A. Van Zeeland, R. E. Waltz, G. Wang, A. E. White, Z. Yan, X. Yuan, and Y. B. Zhu. Energetic ion transport by microturbulence is insignificant in tokamaksa). *Physics of Plasmas*, 20(5):–, 2013.

[23] A. Bovet, I. Furno, A. Fasoli, K. Gustafson, and P. Ricci. Investigation of fast ion transport in torpex. *Nuclear Fusion*, 52(9):094017, 2012.

[24] R. S. Iroshnikov. The turbulence of a conducting fluid in a strong magnetic field. *Astron. Zh.*, 40:742, 1963. English Translation: Sov. Astron., 7 566 (1964).

[25] R. H. Kraichnan. Inertial range spectrum of hyromagnetic turbulence. *Phys. Fluids*, 8:1385–1387, 1965.

[26] D. J. Thuecks, C. A. Kletzing, F. Skiff, S. R. Bounds, and S. Vincena. Tests of collision operators using laboratory measurements of shear Alfvén wave dispersion and damping. *Phys. Plasmas*, 16(5):052110–+, May 2009.

[27] C. A. Kletzing, D. J. Thuecks, F. Skiff, S. R. Bounds, and S. Vincena. Measurements of Inertial Limit Alfvén Wave Dispersion for Finite Perpendicular Wave Number. *Phys. Rev. Lett.*, 104(9):095001–+, March 2010.

[28] D. W. Auerbach, T. A. Carter, S. Vincena, and P. Popovich. Resonant drive and nonlinear suppression of gradient-driven instabilities via interaction with shear Alfvén waves. *Phys. Plasmas*, 18(5):055708–+, May 2011.

[29] G. G. Howes and K. D. Nielson. Alfvén wave collisions, the fundamental building block of plasma turbulence. I. Asymptotic solution. *Phys. Plasmas*, 20(7):072302, July 2013.

[30] K. D. Nielson, G. G. Howes, and W. Dorland. Alfvén wave collisions, the fundamental building block of plasma turbulence. II. Numerical solution. *Physics of Plasmas*, 20(7):072303, July 2013.

[31] G. G. Howes, K. D. Nielson, D. J. Drake, J. W. R. Schroeder, F. Skiff, C. A. Kletzing, and T. A. Carter. Alfvén wave collisions, the fundamental building block of plasma turbulence. III. Theory for experimental design. *Physics of Plasmas*, 20(7):072304, July 2013.

[32] G. G. Howes, D. J. Drake, K. D. Nielson, T. A. Carter, C. A. Kletzing, and F. Skiff. Toward Astrophysical Turbulence in the Laboratory. *Phys. Rev. Lett.*, 109(25):255001, December 2012.

[33] D. J. Drake, J. W. R. Schroeder, G. G. Howes, C. A. Kletzing, F. Skiff, T. A. Carter, and D. W. Auerbach. Alfvén wave collisions, the fundamental building block of plasma turbulence. IV. Laboratory experiment. *Physics of Plasmas*, 20(7):072901, July 2013.

[34] Yuhou Wang, Walter Gekelman, Patrick Pribyl, and Konstantinos Papadopoulos. Scattering of magnetic mirror trapped fast electrons by a shear alfvén wave. *Phys. Rev. Lett.*, 108:105002, Mar 2012.

[35] Y. Wang, W. Gekelman, and P. Pribyl. Hard x-ray tomographic studies of the destruction of an energetic electron ring. *Review of Scientific Instruments*, 84(5):053503, 2013.

[36] Y. Wang, W. Gekelman, P. Pribyl, and K. Papadopoulos. Enhanced loss of magnetic-mirror-trapped fast electrons by a shear alfvén wave. *Physics of Plasmas*, 21(5):055705, 2014.

[37] O. A. Rosso, H. A. Larrondo, M. T. Martin, A. Plastino, and M. A. Fuentes. Distinguishing noise from chaos. *Phys. Rev. Lett.*, 99:154102, Oct 2007.

[38] Christoph Bandt and Bernd Pompe. Permutation entropy: A natural complexity measure for time series. *Phys. Rev. Lett.*, 88:174102, Apr 2002.

[39] D. C. Pace, M. Shi, J. E. Maggs, G. J. Morales, and T. A. Carter. Exponential frequency spectrum and lorentzian pulses in magnetized plasmas. *Physics of Plasmas*, 15(12):122304, 2008.

[40] J E Maggs and G J Morales. Exponential power spectra, deterministic chaos and lorentzian pulses in plasma edge dynamics. *Plasma Physics and Controlled Fusion*, 54(12):124041, 2012.

[41] J. E. Maggs and G. J. Morales. Origin of lorentzian pulses in deterministic chaos. *Phys. Rev. E*, 86:015401, Jul 2012.

[42] J E Maggs and G J Morales. Permutation entropy analysis of temperature fluctuations from a basic electron heat transport experiment. *Plasma Physics and Controlled Fusion*, 55(8):085015, 2013.

[43] J E Maggs, T L Rhodes, and G J Morales. Chaotic density fluctuations in l-mode plasmas of the diii-d tokamak. *Plasma Physics and Controlled Fusion*, 57(4):045004, 2015.

[44] S. T. Vincena, G. J. Morales, and J. E. Maggs. Effect of two ion species on the propagation of shear Alfvén waves of small transverse scale. *Physics of Plasmas*, 17(5):052106, 2010.

[45] S. T. Vincena, W. A. Farmer, J. E. Maggs, and G. J. Morales. Laboratory realization of an ion-ion hybrid alfvén wave resonator. *Geophysical Research Letters*, 38(11):L11101, 2011.

[46] W. A. Farmer and G. J. Morales. Cherenkov radiation of shear alfvén waves in plasmas with two ion species. *Physics of Plasmas*, 19(9):092109, 2012.

[47] S. T. Vincena, W. A. Farmer, J. E. Maggs, and G. J. Morales. Investigation of an ion-ion hybrid alfvén wave resonator. *Physics of Plasmas*, 20(1):012111, 2013.

[48] W. A. Farmer and G. J. Morales. Propagation of shear alvén waves in two-ion species plasmas confined by a nonuniform magnetic field. *Physics of Plasmas*, 20(8):–, 2013.

[49] W. A. Farmer and G. J. Morales. The ion-ion hybrid alfvén resonator in a fusion environment. *Physics of Plasmas*, 21(6):062507, 2014.

[50] Eric E. Lawrence and Walter Gekelman. Identification of a quasiseparatrix layer in a reconnecting laboratory magnetoplasma. *Phys. Rev. Lett.*, 103:105002, Sep 2009.

[51] W Gekelman, E Lawrence, A Collette, S Vincena, B Van Compernolle, P Pribyl, M Berger, and J Campbell. Magnetic field line reconnection in the current systems of flux ropes and alfvén waves. *Physica Scripta*, 2010(T142):014032, 2010.

[52] B. Van Compernolle, W. Gekelman, P. Pribyl, and C. M. Cooper. Wave and transport studies utilizing dense plasma filaments generated with a lanthanum hexaboride cathode. *Physics of Plasmas*, 18(12):123501, 2011.

[53] Walter Gekelman, Bart Van Compernolle, Tim DeHaas, and Stephen Vincena. Chaos in magnetic flux ropes. *Plasma Physics and Controlled Fusion*, 56(6):064002, 2014.

[54] P. W. Terry. Suppression of turbulence and transport by sheared flow. *Rev. Mod. Phys.*, 72:109–165, 2000.

[55] J. E. Maggs, T. A. Carter, and R. J. Taylor. Transition from bohm to classical diffusion due to edge rotation of a cylindrical plasma. *Phys. Plasmas*, 14:052507, 2007.

[56] T. A. Carter and J. E. Maggs. Modifications of turbulence and turbulent transport associated with a bias-induced confinement transition in the large plasma device. *Phys. Plasmas*, 16:012304, 2009.

[57] D. A. Schaffner, T. A. Carter, G. D. Rossi, D. S. Guice, J. E. Maggs, S. Vincena, and B. Friedman. Modification of turbulent transport with continuous variation of flow shear in the large plasma device. *Phys. Rev. Lett.*, 109:135002, 2012.

[58] D. A. Schaffner, T. A. Carter, G. D. Rossi, D. S. Guice, J. E. Maggs, S. Vincena, and B. Friedman. Turbulence and transport suppression scaling with flow shear on the large plasma device. *Phys. Plasmas*, 20:055907, 2013.

[59] G. M. Staebler, R. E. Waltz, J. Candy, and J. E. Kinsey. New paradigm for suppression of gyrokinetic turbulence by velocity shear. *Phys. Rev. Lett.*, 110:055003, Jan 2013.

[60] P. Popovich, M. V. Umansky, T. A. Carter, and B. Friedman. Analysis of plasma instabilities and verification of bout code for linear plasma device. *Phys. Plasmas*, 17:102107, 2010.

[61] P. Popovich, M. V. Umansky, T. A. Carter, and B. Friedman. Modeling of plasma turbulence and transport in the large plasma device. *Phys. Plasmas*, 17:122312, 2010.

[62] M. V. Umansky, P. Popovich, T. A. Carter, B. Friedman, and W. M. Nevins. Numerical simulation and analysis of plasma turbulence the large plasma device. *Phys. Plasmas*, 18:055709, 2011.

[63] B. Friedman, M. V. Umansky, and T. A. Carter. Grid convergence study in a simulation of lapd turbulence. *Contrib. Plasma Phys.*, 52:412–416, 2012.

[64] B. Friedman, T. A. Carter, M. V. Umansky, D. Schaffner, and B. Dudson. Energy dynamics in a simulation of lapd turbulence. *Phys. Plasmas*, 19:102307, 2012.

[65] B. Friedman, T. A. Carter, M. V. Umansky, D. Schaffner, and I. Joseph. Nonlinear instability in simulations of large plasma device turbulence. *Phys. Plasmas*, 20:055704, 2013.

[66] B. Friedman and T.A. Carter. Linear technique to understand non-normal turbulence applied to a magnetized plasma. *Phys. Rev. Lett.*, 113:025003, 2014.

[67] B. Friedman and T.A. Carter. A non-modal analytical method to predict turbulent properties applied to the Hasegawa-Wakatani model. *Phys. Plasmas*, 22:012307, 2015.

[68] J. F. Drake, A. Zeiler, and D. Biskamp. Nonlinear self-sustained drift-wave turbulence. *Phys. Rev. Lett.*, 75:4222, 1995.

[69] D. Biskamp and A. Zeiler. Nonlinear instability mechanism in 3d collisional drift-wave turbulence. *Phys. Rev. Lett.*, 74:706, 1995.

[70] B. D. Scott. Self-sustained collisional drift-wave turbulence in a sheared magnetic field. *Phys. Rev. Lett.*, 65:3289, 1990.

[71] B. Van Compernolle, G. J. Morales, J. E. Maggs, and R. D. Sydora. Laboratory study of avalanches in magnetized plasmas. *Phys. Rev. E*, 91:031102, Mar 2015.