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 have involved individuals affiliated with 17 different institutions: 16 professors, 14 Ph.D. scientists and 31 graduate 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 74 peer-reviewed publications. 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, 17 students have earned Ph.D.s based on work performed at the BaPSF, and 2 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 junior 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/NJIT) is taking advantage of the BaPSF to develop a similar career trajectory. It is expected that other junior faculty members will similarly benefit from the BaPSF capabilities during the next 5 years of operation.

This proposal requests funds both for operation of the user facility (100% of the NSF request, including outreach as part of facility operations, and 82% of the DOE request) and a research program led by BaPSF staff (18% of the DOE request). 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. As a result of their research programs, the BaPSF research staff are much more effective in their user support roles: they are active contributors rather than simply machine operators.

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. 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 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 be 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 later. 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. Breizman (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. It is 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

This section presents highlights of selected research programs from both the external user groups and the local group.

Research Highlights – External user groups:

Highlights of external user research, including campaigns, are provided as examples of research enabled by (but not fully supported by) the operational budget of the BaPSF. It should be noted that the research budget of the BaPSF has also supported external user research; in particular some campaigns and theory-driven studies have benefited from funding for UCLA graduate students who have participated in those projects. Over the past 5 years, there have been 4 independent experimental user groups, 7 theory-driven studies and 3 topical campaigns. The leaders of these various efforts and their affiliated institutions are listed here. Highlights from 5 of these research programs follow; brief descriptions of all external user research is offered in the Appendix.

Independent experimental user groups: (1) C. Niemann (UCLA); (2) C. Kletzing, F. Skiff, G. Howes (University of Iowa); (3) D. Bui, Y. Song (Tri Alpha Energy); (4) 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) D. D'Ippolito, J. Myra (Lodestar Corp); (5) A. Streltsov (Embry-Riddle University); (6) Li-Jen Chen (U. New Hampshire); (7) D. Savin, M. Hahn (Columbia).

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-produced 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 a high-energy glass laser. A blow-off plasma was created that propagated at super Alfvénic speeds across a 300G external magnetic field in which a preexisting H^+ plasma was confined.

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.

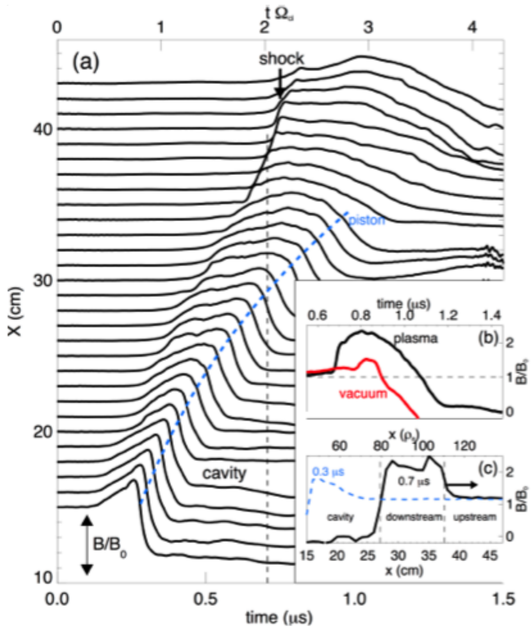

Figure 1: a) Magnetic stack plots of B_z as a function of time for various distances from the target. (b) Comparison of $B_z(t)$ at $x = 35$cm with (black) and without (red) the ambient plasma. (c) Structure of the pulse before ($t = 0.3\ \mu$s) and after a shock is formed.

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 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].

It should be noted that this result was enabled by the higher-density plasma operation accessible with the new 20 cm LaB_6 secondary cathode added over the previous funding cycle. Through increasing the density in a core region by a factor of ~ 10 over the Barium Oxide plasma source the ion skin depth was reduced and the formation of the shock was successfully observed.

Resonant interactions between energetic electrons and whistler waves (J. Bortnik (UCLA/NJIT), 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

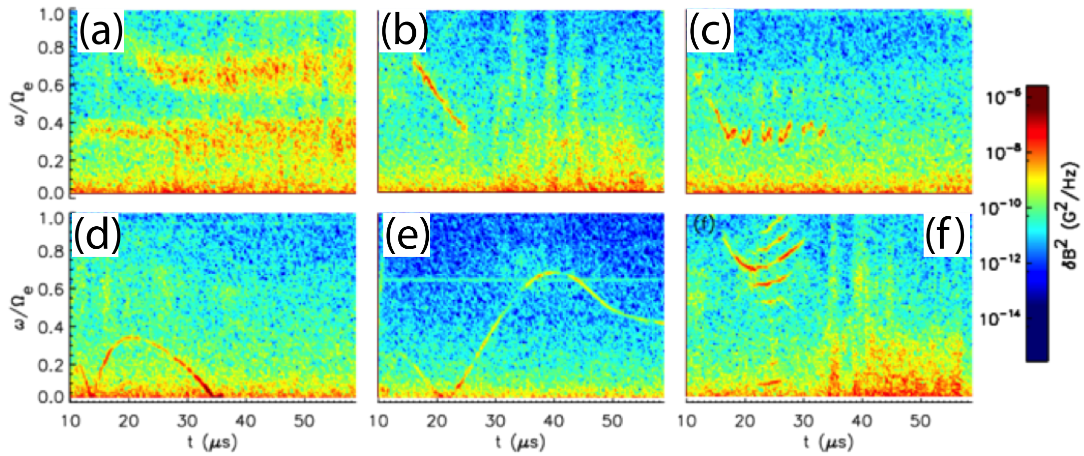

Figure 2: Examples of spectrograms of whistler wave excitation. (a) broadband waves, (b) falling tone, (c) multiple consecutive chirps, (d) double hook, (e) long rising and falling tone, (f) chirps at multiple frequencies simultaneously

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 broadband 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 25 keV, 10 A 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 Alfvén 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

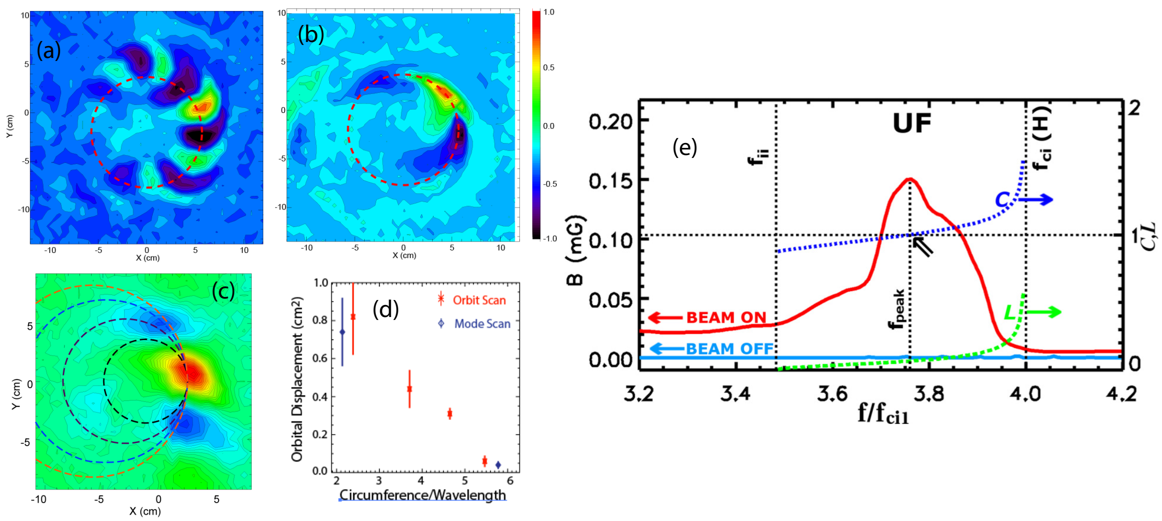

Figure 3: (a), (b), (c) Measured correlation function for electrostatic fluctuations in LAPD, with cartoon of test ion orbit superposed. (d) Variation of orbital displacement of test ions with $\rho_{\text{fast}}/\lambda_\perp$, where $\lambda_\perp$ is the perpendicular wavelength of the electrostatic fluctuations. (e) In the presence of an energetic H^+ beam, amplification of magnetic fluctuations is observed. The $n = 1$ DICR condition is satisfied (marked by the double arrow) near f_{peak}, suggesting the excitation of shear Alfvén waves through DICR of the ion beam.

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 micro-turbulence structure along its large gyro and drift orbits. 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 wave number 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 wave number 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].

Another aspect of the campaign has been the study of the interaction between the intense fast ion beam (25 keV, 10A) with the LAPD plasma and the generation of waves. Experiments were carried out to explore the excitation of waves by this intense ion beam, which is injected with varying pitch angles from the far end of LAPD (away from the BaO cathode source). With injection of H^+ fast ions into a He plasma, excitation of waves in three frequency bands is observed: below the He ion cyclotron frequency, between the ion-ion hybrid frequency and the H cyclotron frequency (the background plasma was a mix of 92% He and 8% H), and above the H cyclotron frequency, reaching up to the lower hybrid frequency. The fluctuations in the second band (above the ion-ion hybrid frequency) have been identified as shear Alfvén waves; the spectrum of these fluctuations are shown in Fig. 3(e). The peak of the fluctuation spectrum in this band lies at the frequency where the condition for Doppler-shifted Ion Cyclotron Resonance (DCIR) is met [24].

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 the successful study of the fundamental nonlinear interaction underlying astrophysical plasma turbulence, Alfvén wave collisions. Early research on incompressible MHD turbulence in the 1960s [25, 26] 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.

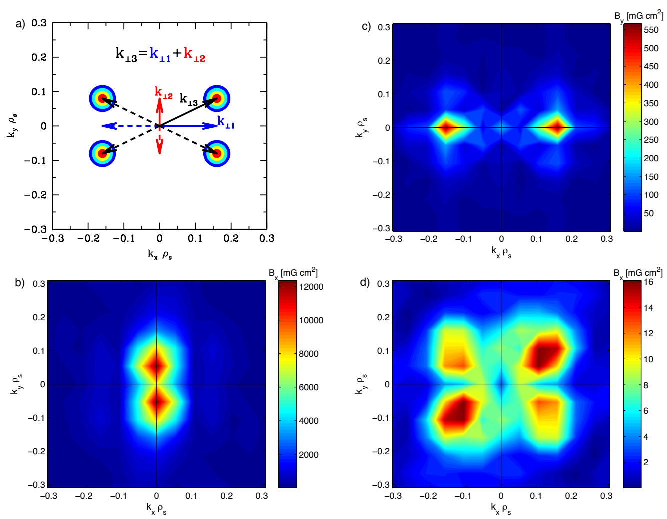

Figure 4: (a) Diagram of $\mathbf{k}_{\perp 1}$ for the ASW antenna (blue) and $\mathbf{k}_{\perp 2}$ for the Loop antenna (red). Bullseyes indicate predicted power distribution of the nonlinear product. Colormaps of $\delta B_x(k_x,k_y)$ for: (b) the Loop antenna by itself, (c) the ASW antenna by itself, (d) 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 [27, 28] from one end of the LAPD chamber, and another Alfvén wave using UCLA's Loop antenna [29] from the other end. Theoretical calculations of the nonlinear energy transfer in the weakly nonlinear limit [30], along with validating gyrokinetic numerical simulations [31], guided a novel experimental design [32] that lead to the successful experimental verification of the physics of Alfvén wave collisions in the laboratory

[33, 34], 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) (D. Papadopoulos, T. Antonsen (Univ. Maryland), Y. Wang, W. Gekelman, P. Pribyl, G. Morales (UCLA))

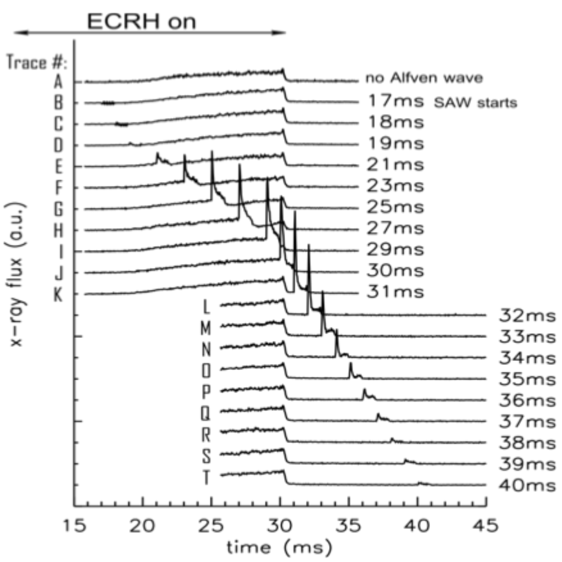

Figure 5: Time series of measured x-ray flux Trace A is measured without launching the SAW. In traces B-T a shear Alfvén wave pulse, starting at different times, as labeled, is launched.

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 (100 keV) is generated in a magnetic mirror section (mirror ratio ≈ 2, length = 3.5m) 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 (400 G 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 [35]. 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 is detected when the Alfvén wave is present. 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. 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, which is limited by collisional scattering into the loss cone. 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 where the hot electrons go after having interacted with the wave [36]. Most of the fast electrons strike the waveguide, which is very close to the plasma edge. Electrons are also lost to a mesh anode at the end of the device. These have been scattered into the loss cone [37].

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 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 [38] 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 [39] 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 [40–43]. 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 [44].

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 [45–49]. 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

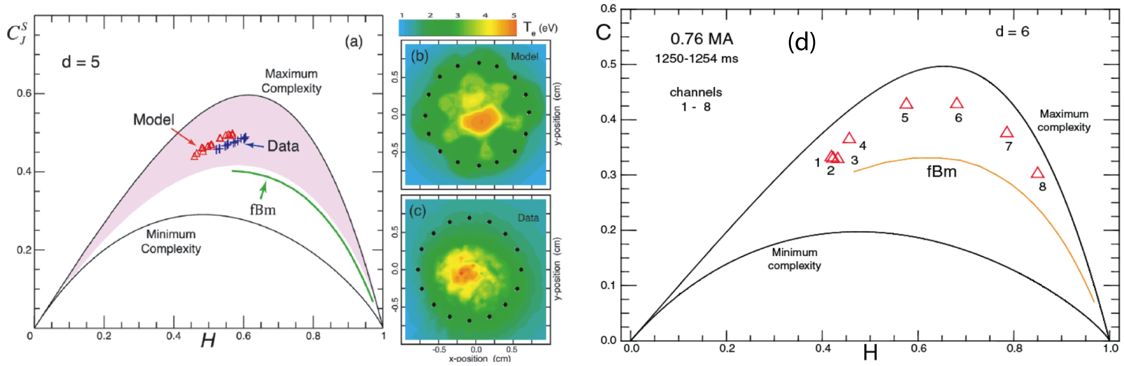

Figure 6: (a-c) C-H plane analysis of data in LAPD experiment and of prediction of a chaotic advection model shows LAPD dynamics are chaotic. (d) C-H plane analysis of Doppler-backscattering (DBS) from DIII-D shows that the signals from all the channels (different radii) are in the chaotic region, as in the LAPD experiment.

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, as illustrated in Fig. 7.

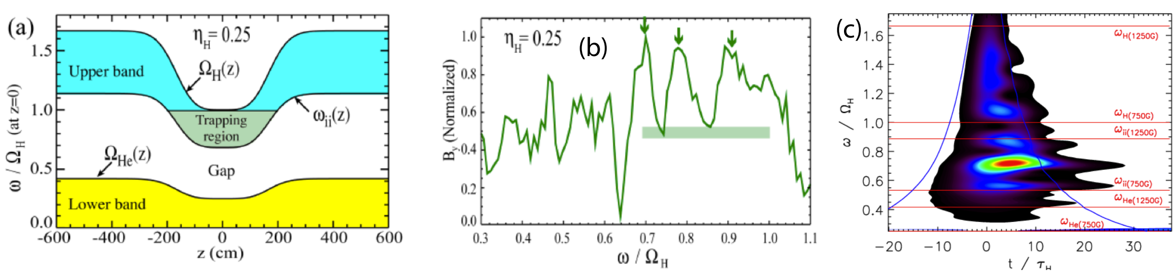

Figure 7: (a) Axial variation of resonator in LAPD for a H-He^+ plasma showing propagation bands and gap. (b) Spectrum of magnetic fluctuations inside resonator shows resonator peaks; arrows are theoretically-predicted frequencies of trapped modes. (c) Contours of Morlet wavelet amplitude of magnetic 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 [50].

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 (E. Lawrence) and present (T. DeHaas, D. Hong) have done groundbreaking work on the interaction of magnetic flux ropes.

The first experimental determination [51] 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 8.

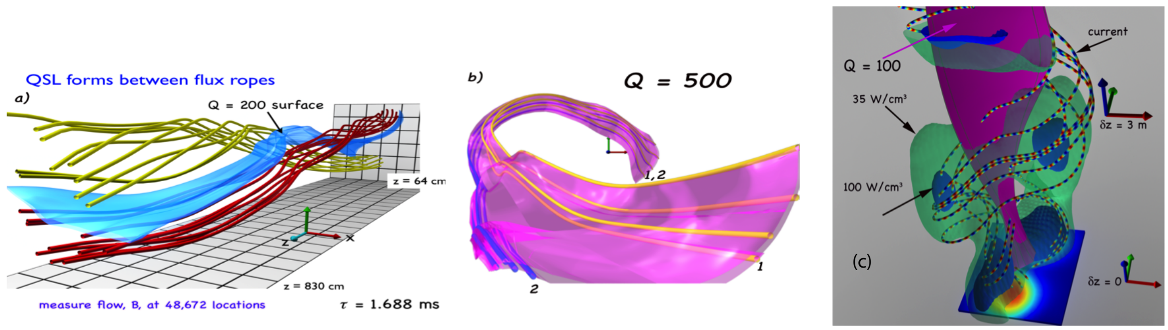

Figure 8: (a) The blue surface is a QSL (Q = 100) which is located between two flux ropes colored red and yellow. The flux ropes are calculated by following field lines through the dense grid of measurement points. (b) A Q = 500 surface with several field lines within it. One set of field lines labeled (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. (c) Bottom is the plasma current in a plane 64 cm from the origin of the ropes. 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.

QSLs have been observed in the collision of two or more flux ropes [52, 53]. 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 8(c) 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 measured by integrating the electric field along magnetic field lines.

Magnetic fluctuations associated with flux ropes in LAPD were analyzed using the Bandt-Pompe approach to search for chaotic behavior [38, 39]. The magnetic fluctuation time signals do exhibit chaotic behavior, in particular when, in addition to the flux rope, there are large amplitude Alfvén waves present (generated by the Alfvén wave MASER [54, 55]) [56].

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 [57]. However a complete, quantitatively correct theoretical model of transport suppression by sheared flow is still lacking. 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 [58, 59]. 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) [58].

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 9(a,b) 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 [60]. 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.

LAPD experimental data has been compared to a number of analytical theoretical models of shear suppression [61]. The ability to continuously vary the edge flow shear in LAPD allowed the collection of data for both the weak ($\gamma_s \tau_{\rm ac}$ 1) and strong ($\gamma_s \tau_{\rm ac}$ 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 [62].

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

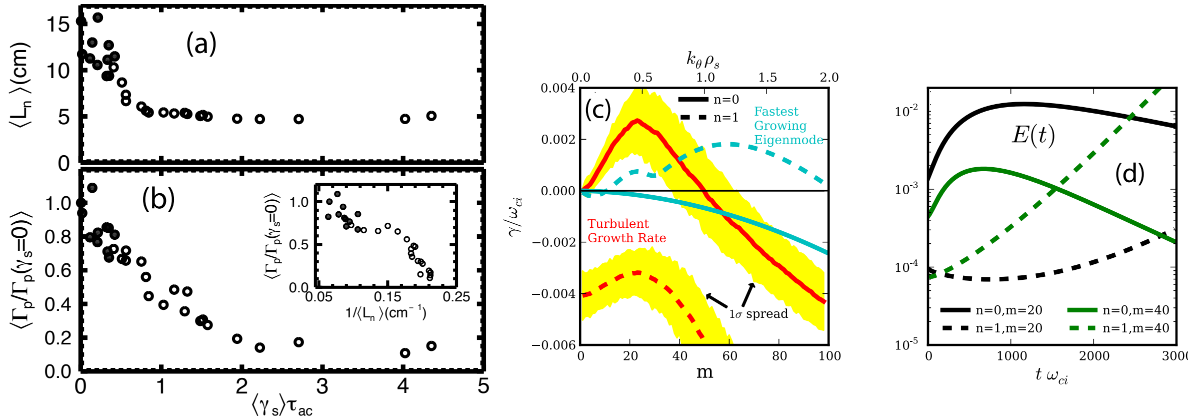

Figure 9: (a) Gradient scale length versus shearing rate. (b) Particle flux normalized to no-shear flux as a function of normalized shearing rate. Filled symbols represent points with flow in the ion diamagnetic direction. Inset: Measured turbulent particle flux versus gradient scale length. (c) Linear evolution of energy starting from a turbulent initial state. The $n = 0$ curves have an initial period of transient growth before exponentially decaying. (d) Linear 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.

amplitude perturbations can still excite turbulence. 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 [63–66]. Even though the resistive drift-Alfvén wave is linearly unstable, the simulations reveal that a nonlinear instability controls the saturated turbulent state [67–70], as shown in Figure 9(c). Consistent with this observation, transient growth of linearly-stable flute-like ($k = 0$) modes is observed, as shown in Figure 9(d).

A similar conclusion was previously reached by authors examining tokamak edge turbulence simulations [71–73]. 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 [69, 70].

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

Facility Development: Cathode Upgrade

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 (LaB_6) based cathode. Large area LaB_6 cathodes have been developed over the last funding period by the UCLA group (see Facilities & Infrastructure for more details) and offer many advantages to BaO cathodes, including access to important new parameter regimes and significant operational advantages.

LaB_6 cathodes offer far more emission current density, and therefore can produce higher density and temperature plasmas, than BaO cathodes. Recently, a 20cm LaB_6 cathode has been installed on LAPD, 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); see Fig. 10. 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 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 (see Figure 10(c)). Table 1 gives a comparison of plasma parameters achievable in the BaO and LaB_6 cathode plasmas. There is some flexibility in operating the LaB_6 source, in particular the emissivity of the cathode can be controlled through raising or lowering the temperature. By lowering the temperature and the emissivity, plasmas with parameters similar to the present BaO cathode plasmas can be produced. Part of the local group research time would be dedicated to developing operational regimes using a new LaB_6 plasma source. In particular, developing lower collisionality regimes is of interest. Plasmas created so far using the smaller LaB_6 sources have similar electron collisionality to BaO plasmas: the electron temperature is higher, but the potential gains in collisionality are reduced by increased density. The ion collisionality is lowered due to the substantial increase in ion temperature in the new source. It may be possible to develop an operational condition where the plasma density is lowered (perhaps similar to BaO plasmas) but with increased electron temperature; developing this regime (perhaps using high temperature cathode but with low fill pressure) will be a focus of future work by the local group.

The parameters accessible using a LaB_6 source opens up a range of possible new research directions using LAPD. The higher density reduces the ion skin depth scale to be smaller than the perpendicular size of the plasma. This fact allowed the first observation of a magnetized collisionless shock in LAPD using the small LaB_6 secondary source [2, 3]. The installation of a larger LaB_6 source will allow further studies of the shock properties by allowing more room for the shock to develop and evolve. Studies of magnetic reconnection and magnetic flux ropes have also been enabled by the development of LaB_6 cathodes. Future studies would make use of the larger plasma source to generate longer current sheets for exploration of reconnection and current sheet instabilities. The increased density also enables studies of compressional Alfvén waves by shortening their perpendicular wavelength to fit inside of the LAPD plasma. Studies of fast wave physics will be the subject of local group research as well as a new Campaign.

LaB_6 cathode-produced plasmas provide the opportunity to study the linear and nonlinear physics of

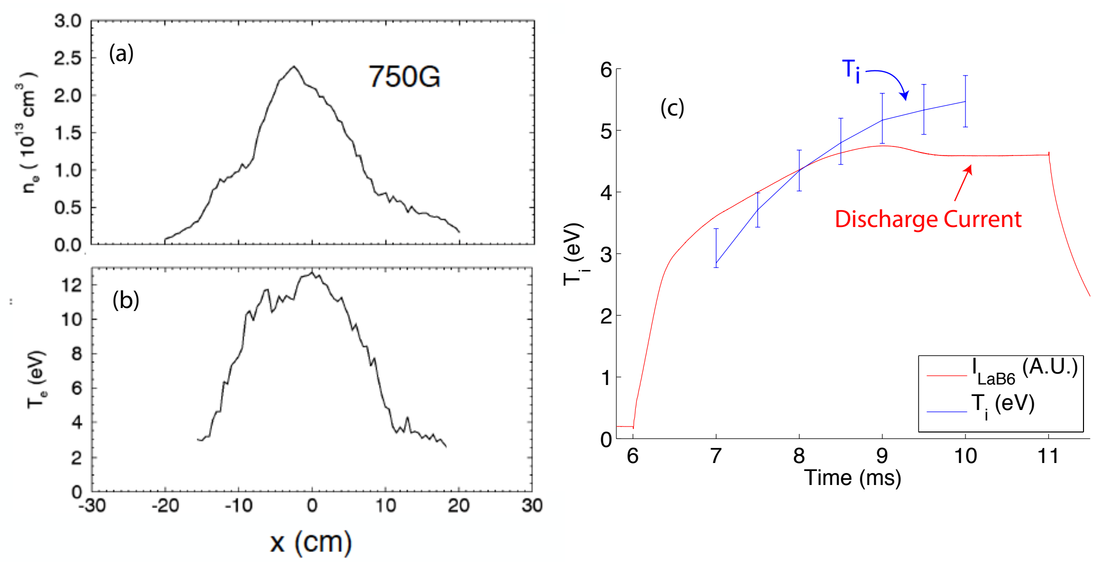

Figure 10: (a) Density and (b) Electron temperature profiles for plasmas generated with the 20cm LaB_6 secondary cathode in LAPD. (c) Time history of the LaB_6 cathode discharge current and ion temperature (measured spectroscopically).

Parameter	BaO (1 kG)	LaB_6 (1 kG)	LaB_6 (400G)	LaB_6 (125G)
Density (cm^{-3})	2×10^{12}	2×10^{13}	2×10^{13}	2×10^{13}
Electron temperature (eV)	5-10	10-15	10-15	10-15
Ion temperature (eV)	$\lesssim 1$	~ 5	~ 5	~ 5
Electron gyroradius (mm)	0.05	0.09	0.23	0.74
Ion gyroradius (cm)	0.2	0.46	1.4	3.6
Ion sound gyroradius (cm)	0.5	0.79	2.0	6.3
c/ω_{pe} (mm)	4	1.2	1.2	1.2
c/ω_{pi} (cm)	32	10	10	10
Ion cyclotron frequency (kHz)	380	380	152	48
Electron collision frequency (MHz)	3	10	10	10
Ion collision frequency (kHz)	300	100	100	100
Typical Alfvén wave frequency (kHz)	200	200	100	25
Plasma Beta	4×10^{-4}	1.6%	10%	~ 1

Table 1: Typical parameters for helium discharges in LAPD.

Alfvén waves in plasmas with $T_i \sim T_e$ and at higher beta ($\beta \sim 1$ is possible through reduced magnetic field). With hot ions, finite ion Larmor radius effects are expected to modify propagation of oblique Alfvén waves [74, 75]. With increased plasma beta (meaning $v_A \sim v_{th,i}$), kinetic damping of Alfvén waves can be due to resonant interactions with ions: ion Landau damping due to parallel electric fields in the wave or ion Barnes or Transit Time Magnetic Pumping damping due to compressive fluctuations modifying the background magnetic field [76]. The nature of nonlinear interactions between Alfvén waves is modified by increased ion temperature and increased plasma beta; for example, ion sound waves should be heavily damped with $T_i \sim T_e$, which impacts parametric decay. Ion temperature anisotropy may be driven in LAPD through using auxillary heating (cyclotron heating using fast or shear Alfvén waves) or through driving flow into an expanding magnetic field. This, coupled with the large achievable β, may allow the study of instabilities such as the mirror [77] and firehose [78] which are known to be important in the solar wind [79, 80] and may be important in other astrophysical settings (such as in accretion disks [81]). This new regime will be the subject of study by the local group as well as external users; the new Solar Wind campaign (described later) will leverage the new capabilities provided by the upgraded source.

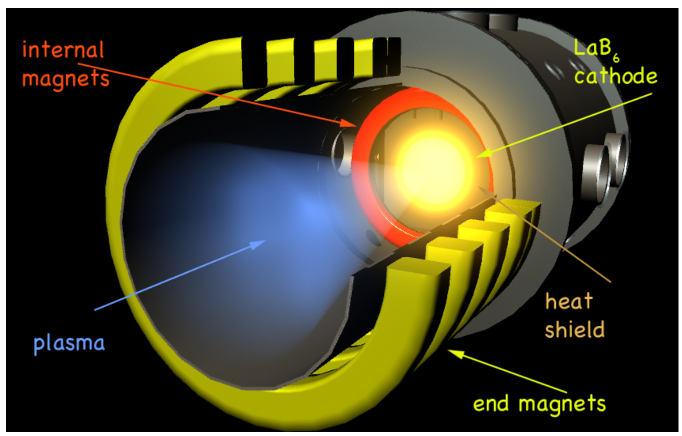

Figure 11: Conceptual design for new primary LaB_6 cathode source with internal magnets for LAPD

Operationally, LaB_6 cathodes are far more robust than BaO cathodes. BaO cathodes are sensitive to Oxygen; any significant exposure to Oxygen can “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). LaB_6 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 LaB_6 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. BaO cathodes are manufactured with thin sprayed-on coatings on metal (nickel for the LAPD cathode). These coatings erode with time due to ion bombardment and must be replaced every 3-4 months. Additionally, the erosion is generally not uniform, resulting in a plasma profile that may vary with time as the coating changes. LaB_6 cathodes are made with thick (1/4”) pieces of sintered material; while erosion does occur, the cathodes last significantly longer and emission tends to remain uniform. A prototype LaB_6 plasma source was operated at 1 Hz continuously for 1 year in the ETPD without need for a maintenance opening.

We plan to construct a new LaB_6 cathode as a permanent replacement for the current 75cm diameter BaO cathode. Due to the significant power required to heat LaB_6 to optimal emission temperature (1800C), it is not practical to build a 75cm large cathode. Instead, a 40cm source will be constructed based on the proven graphite heater and LaB_6 cathode technology developed by the UCLA group [82]. This smaller source will then be used to create a larger (60cm diameter) plasma through expansion of the magnetic field from the source region into the main chamber. An internal (to the vacuum chamber) magnet will be fabricated to strongly magnetize the source region (up to 6 kG) in order to produce $\sim$60cm diameter plasmas in the main chamber at nominal magnetic field values (up to 2 kG). A rendering of the new plasma source is shown in Fig. 11. Funding in the amount of $600k is requested in the first year to purchase components for the new cathode source, including internal magnets and power supplies for the magnets and the new discharge source. Construction will be carried out over the first two years of the new award, led by Assoc. Director Prof. Gekelman. The fabrication of the new source will not impact operations until installation at the end of the second year. It is anticipated that a 1 month shutdown period will be required to install the new source.

Proposed Research - Local Group

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 [83]. 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.

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

The UCLA group will continue the successful research program investigating the physics of three-dimensional current systems and reconnection. Experiments using both interacting flux ropes and long current sheets are planned; both will be produced using LaB_6 cathodes.

Experiments with interacting flux ropes will focus on more quantitative characterization of the reconnection process. The reconnection rate will be characterized using measures developed to evaluate simulations of three-dimensional reconnection [84, 85], e.g., through computing the line integral of the electric field along the interface between the flux ropes. Direct measurements of the total electric field, using a combination of emissive and electric dipole probes. Scaling of the reconnection rate with experimental parameters can then be investigated and the connection between the well characterized QSL and the rate can be established (how does the reconnection rate scale with Q?). Energy conversion by the reconnection process will also be a focus. Dissipation, electron and ion heating, and the production of flows will be studied. Initial measurements of the parallel electric field have revealed an anomalously high resistivity in interacting flux rope experiments. The source of this resistivity will be investigated, focusing on the role of instabilities through measurements of high frequency fluctuations.

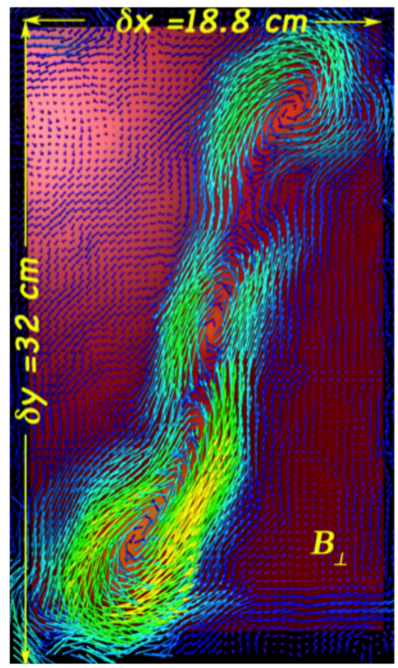

Figure 12: Vectors of perpendicular magnetic field in a plane 6.8 m from the LaB_6 source. Three magnetic islands are visible as O-points in the magnetic field.

Experiments using current sheets will be performed as part of a theory-driven external user project led by W. Daughton (LANL). A UCLA graduate student will participate in this project for their Ph.D. research (and as such this effort will be partly funded by the research portion of this proposal). Initial experiments have been done where a current sheet is generated by using a graphite "mask" for the secondary LaB_6 cathode. The mask allows current to flow through a long, thin slit, forming a current sheet with aspect ration of ~ 10. The sheet is observed to tear into three separate O-points, as shown in Fig. 12.

Future work will investigate the parametric dependence of the observed tearing. Is there a threshold for observing the break-up in the current sheet, perhaps related to the aspect ratio or the length, normalized to $c/\omega_{\rm p,i}$ (currently ~ 3) or ρ_i (currently ~ 60)? Simulations, using the VPIC code [86], are being performed to compare to the experimental measurements and will be used to guide further experiment. Focus will be given to exploring any connection to the "plasmoid" instability [87, 88]. Initial measurements of parallel electric fields and currents in these experiments indicate that the resistivity is anomalous, up to 30 times the Spitzer resistivity. The cause of this anomaly will be investigated, starting with measurements of high frequency fluctuations in the current sheet.

Studies of waves, instabilities and turbulence facilitated by the new LaB_6 plasma source

The BaPSF group will spend considerable effort studying plasmas created using the new LaB_6 sources. This will begin through continued studies using the existing 20 cm secondary LaB_6 source and extend after the commissioning of the new primary LaB_6 plasma source that will be constructed through support requested in this proposal. This effort will seek to establish the range of operating conditions achievable using LaB_6 sources and extend capabilities such as, e.g., wave launching and flow control to these new conditions. These efforts are expected to lay the groundwork for external users and campaigns to exploit the new plasma sources as well as make advances in fundamental plasma physics.

Pressure-gradient-driven turbulence and transport in increased β, warm ion plasmas (Carter, Vincena)

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 LaB_6 plasma source but will make full use of the new larger area LaB_6 primary plasma source. LaB_6 sources 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 (see Table 1). 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. Electromagnetic effects at finite β are expected to introduce a number of significant changes to the plasma turbulence, including changes to linear (e.g., coupling to Alfvén waves [89–92]) and nonlinear properties (e.g., changes in saturation mechanisms [93–95]). As β increases, the interaction between Maxwell and Reynolds stress leads to modifications of the turbulent drive of cross-field flows [96, 97]. Magnetic transport of particles may become important as β is increased [98, 99].

In addition, the production of warm ions provides an opportunity to investigate ion kinetic effects on the turbulence. 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; this work will be carried out in collaboration with Prof. F.

Jenko (UCLA). 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. This work has existing support from the NSF-DOE partnership, which will continue through 2018 (PIs Carter and Jenko). This proposal would leverage this existing support and add additional resources in the form of BaPSF research staff time.

Physics of compressional Alfvén waves in LAPD (Vincena, Tripathi, Van Compernolle)

Compressional Alfvén waves are observed in many natural and laboratory plasmas: e.g., in the Earth's magnetosphere, where they might play a role in accelerating radiation belt particles [100]; and in tokamaks, where they are excited by fast ions and may contribute to transport of fast ions and of thermal energy [101]. Compressional Alfvén waves in the ion cyclotron range of frequencies (ICRF) are an important tool in heating magnetically confined plasmas; e.g., ITER will rely on substantial ICRF heating power to achieve its mission [102]. In the BaO produced plasma in LAPD, compressional Alfvén waves are typically evanescent; the wavelength at the ion cyclotron frequency is comparable to the ion skin depth, which is as large as 50 cm (comparable to the diameter of the LAPD plasma). With increased density, this scale length becomes much shorter, allowing the study of these important waves in LAPD.

Initial efforts in this area have explored techniques for exciting fast waves in LAPD. A single-strap ICRF antenna has been designed and fast waves have been launched using a low-power driver. We propose to document the properties of fast waves in LAPD, measuring mode structure, dispersion and damping. The behavior of fast waves in plasma with multiple ion species will also be studied, following up on prior studies of shear wave physics in two-ion plasmas [45, 46]. Ultimately this work will help lay the foundation for the planned RF Campaign (described later), where a focus on interaction between the RF and edge plasmas, including generation of RF sheaths, will be a focus.

Linear and nonlinear properties of shear Alfvén waves in increased β, warm ion plasmas (Carter, Gekelman, Van Compernolle, Vincena, Tripathi)

The proposed research would seek to utilize new plasma parameters provided by LaB_6 cathodes in LAPD to significantly extend past studies on the linear and nonlinear physics of Alfvén waves. With warm ions so that $\rho_i \sim \rho_s$, finite Larmor radius effects modify the dispersion relation for kinetic Alfvén waves [75].

As β is increased, the Alfvén velocity is reduced relative to the electron thermal speed; at $\beta_i = 1$, the Alfvén speed and ion thermal speed are comparable. As such, increasing beta should reduce kinetic damping on electrons and eventually increase interaction with ions as beta approaches unity. At high beta, ions can damp the wave via the wave parallel electric field (Landau damping) but also through transit-time magnetic pumping or Barnes damping due to the presence of compressive magnetic fluctuations [76, 103]. The linear theory of shear Alfvén waves at high beta has been explored by a few authors [104, 105]. Using existing Alfvén wave sources, we propose to carefully document the dispersion and damping of shear Alfvén waves in warm ion, increased β plasmas; focusing on variations with β.

Vincena et al. previously performed experiments in LAPD studying the propagation of shear Alfvén waves into a region of decreasing magnetic field (a "magnetic beach") [106]. In these experiments it was found that a large fraction of the damping of the shear wave came before the cyclotron resonant location was reached and that this was due to Landau damping on electrons. The damping was attributed to increasing electron Landau and collisional damping due to the growth of the parallel electric field of the wave as ω/Ω_i became large.

We propose to repeat this experiment at higher plasma beta and with warm ions to explore whether dominant damping on ions can be achieved using the magnetic beach scheme in LAPD. Increased wave power will be used in an attempt to observe ion heating by shear Alfvén waves. With increased beta, Landau damping on electrons should be reduced as $v_{\rm th,e}/v_{\rm A}$ can be increased significantly. At higher beta, ion Landau and Barnes damping may also contribute to wave absorption before the wave arrives at the location of the cyclotron resonance; finite frequency effects will lower the wave phase velocity, allowing the possibility of $v_{\rm phase} \sim v_{\rm th,i}$ for $\beta \sim 1$. Wave power that does get through to the cyclotron resonance should be more effectively absorbed in a plasma with warmer ions.

Additionally, we propose to study beat-wave interactions between co- and counter-propagating shear Alfvén waves, extending previous studies [21, 29, 107–109]. In particular, recent observations of sound wave generation [108, 109] by interacting shear Alfvén waves should be significantly modified with $T_{\rm i} \sim T_{\rm e}$.

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. This proposal does not request funding to fully support the execution of Campaigns. Funding (through participant costs) is requested to run workshops at UCLA (every other year) which will support the development and operation of campaigns. The leaders of each Campaign will guide the submission of proposals to the relevant funding agencies to support the involvement of the user community. Two new Campaigns are developing as of the writing of this proposal; a brief description of each is offered below.

Solar Wind Campaign. This campaign will coordinate research on topics that will address gaps in our understanding of processes in the solar wind. Alfvénic turbulence is observed directly in the solar wind [110, 111], indirectly in the interstellar medium [112] and is thought to play an important role in momentum transport and heating in accretion disks [113]. Work in this area would build on existing efforts, including initial Alfvén single wave-wave interaction studies on LAPD [21, 29, 107–109] and comparisons between astrophysical turbulence simulation codes and LAPD data [114–116]. The generation of a turbulent spectrum of Alfvén waves in LAPD would be a primary target of this effort. Achieving this goal will require a combination of experimental advances (e.g., improved large amplitude antenna design and developing decreased collisionality plasma regimes) and numerical modeling to identify the optimal experimental parameter regime for achieving a driven Alfvén wave turbulent cascade in the laboratory. Additionally, access to increased β, warm ion plasmas may allow for the study of ion temperature anisotropy driven instabilities such as the mirror and firehose. Campaign collaboration would seek to establish techniques to drive anisotropy and perform modeling to identify optimal conditions for observing the instabilities. Prof. Greg Howes (U. Iowa) has agreed to lead this campaign. Prof. Howes will help to organize a workshop to attract researchers interested in participating in this campaign and develop initial campaign research goals. Prof. Howes plans to take a sabbatical at UCLA during Winter and Spring Quarters of 2017 in part to participate in Campaign activities.

RF Physics Campaign. Radiofrequency heating and current drive are essential to the operation of current and future fusion research devices, including ITER [102]. There is a great deal of interest in the fusion community in the interaction between RF waves (fast waves as well as lower-hybrid) with the boundary and scrape-off-layer (SOL) plasma [117, 118]. The efficiency of RF wave coupling and absorption in the core plasma is impacted by processes in edge and SOL, including, e.g., mode-conversion and parametric decay [119, 120]. Near- and far-field sheaths formed by RF rectification can lead to reduced RF coupling efficiency and impurity generation through ion acceleration and sputtering at the antenna and in the divertor [121, 122]. Campaign research will explore the physics of high power RF wave launch in LAPD, with an initial focus on RF sheath generation. Studies of high power fast waves in LAPD is facilitated by the increased density provided by the new LaB_6 cathode. Dr. Rory Perkins (PPPL) has agreed to help lead this Campaign which would involve RF researchers from the fusion community including theory and modeling. The validation of RF sheath models employed in fusion community codes has already been articulated as a goal. At the time of the writing of this proposal, Dr. Perkins and collaborators are working on a white paper outlining research goals. Assuming the white paper is approved, initial scoping study experiments will be carried out prior to a workshop on this Campaign topic.

LAPTAG Outreach Program

The BaPSF sponsors a high school outreach program known as the Los Angeles Physics Teachers Alliance Group (LAPTAG). LAPTAG is now in its 20th year of existence. LAPTAG is run by Prof. W. Gekelman and Dr. P. Pribyl, one of the scientists at BaPSF.

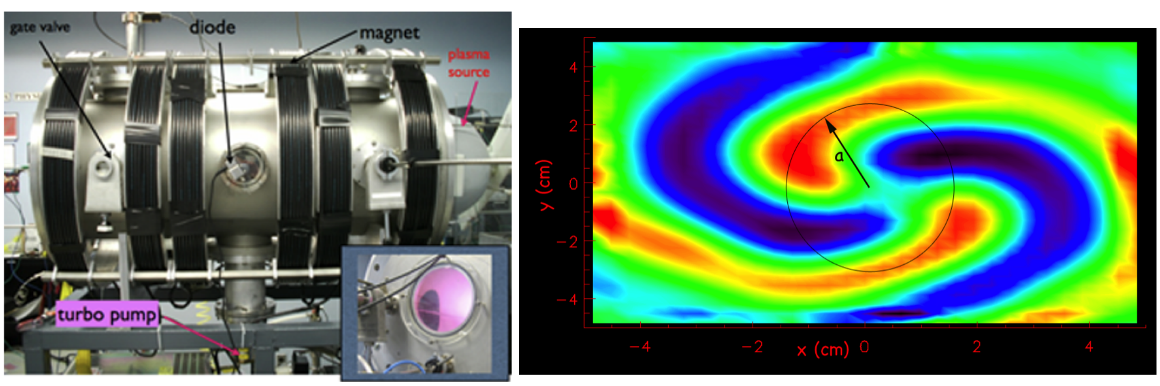

Figure 13: Left: The LAPTAG plasma physics device. Right: Cross-spectral analysis of the cross-field structure of drift waves driven in the device (data taken and analyzed by HS students).

High school students and teachers from the LA area use a small machine constructed especially for them, sometimes out of spare parts from the facility. The LAPTAG device is shown along with representative data on drift waves in Fig. 1. Any high school or community college student is welcome to participate in the program. The students learn lab skills, build electronics and listen to lectures on plasma physics given by BaPSF staff. The LAPTAG students attend scientific meetings, the latest being the Fall 2013 APS-DPP meeting (Denver Colorado) where they presented experimental results on resonance cones and won the "best poster" for undergraduate research. In 2010 they presented data at whistler waves at the Chicago meeting. LAPTAG meets every Saturday and nearly every day during in the summer. Experiments performed by the LAPTAG participants have resulted in publications (with high school student co-authors) in the American Journal of Physics [123, 124]. Presentations of results are made at APS and AAPT meetings. There was an invited paper at the Spring AAPT meeting held in Oxnard, California and others at the 2015 AAPT meetings in Long Beach and at UCLA. LAPTAG has been the subject of several invited talks by Prof. Gekelman as well as an article in APS news [125]. This proposal requests modest funding (in the NSF budget) to support this program, including supplies, fabrication and travel support for participants.

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 junior 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 junior scientists 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. *Geophys. Res. Lett.*, 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, 2014.

[5] R.M. Thorne. Radiation belt dynamics: The importance of wave-particle interactions. *Geophys. Res. Lett.*, 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. *J. Geophys. Res.*, 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, 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, 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, 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. *Rev. Sci. Inst.*, 78(1):013302, 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. *Rev. Sci. Inst.*, 82(9):093501, 2011.

[13] L. Zhao, W. W. Heidbrink, H. Boehmer, R. McWilliams, D. Leneman, and S. Vincena. Measurements of classical transport of fast ions. *Phys. Plasmas*, 12(5):052108, 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. *Phys. Plasmas*, 15(1):012103, 2008.

[15] Y. 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. *Phys. Plasmas*, 15(10):102112, 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). *Phys. Plasmas*, 16(5):055706, 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. *Phys. Plasmas*, 17(9):092103, 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. *Phys. Plasmas*, 19(1):012116, 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 Device. *Phys. Plasmas*, 19(5):055904, 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 Phys. Control. 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 tokamaks. *Phys. Plasmas*, 20(5):056108, 2013.

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

[24] S.K.P. Tripathi, B. Van Compernolle, W. Gekelman, P. Pribyl, and W. Heidbrink. Excitation of shear Alfvén waves by a spiraling ion beam in a large magnetoplasma. *Phys. Rev. E*, 91(1):013109, 2015.

[25] 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).

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

[27] 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, 2009.

[28] 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, 2010.

[29] 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, 2011.

[30] 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, 2013.

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

[32] 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. *Phys. Plasmas*, 20(7):072304, 2013.

[33] 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, 2012.

[34] 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. *Phys. Plasmas*, 20(7):072901, 2013.

[35] 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, 2012.

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

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

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

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

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

[41] J. E. Maggs and G. J. Morales. Exponential power spectra, deterministic chaos and Lorentzian pulses in plasma edge dynamics. *Plasma Phys. Control. Fusion*, 54(12):124041, 2012.

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

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

[44] J. E. Maggs, T. L. Rhodes, and G. J. Morales. Chaotic density fluctuations in L-mode plasmas of the DIII-D tokamak. *Plasma Phys. Control. Fusion*, 57(4):045004, 2015.

[45] 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. *Phys. Plasmas*, 17(5):052106, 2010.

[46] S. T. Vincena, W. A. Farmer, J. E. Maggs, and G. J. Morales. Laboratory realization of an ion-ion hybrid Alfvén wave resonator. *Geophys. Res. Lett.*, 38(11):L11101, 2011.

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

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

[49] W. A. Farmer and G. J. Morales. Propagation of shear Alfvén waves in two-ion species plasmas confined by a nonuniform magnetic field. *Phys. Plasmas*, 20(8):082132, 2013.

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

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

[52] 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.

[53] 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. *Phys. Plasmas*, 18(12):123501, 2011.

[54] J. E. Maggs and G. J. Morales. Laboratory realization of an Alfvén wave maser. *Phys. Rev. Lett.*, 91(3):035004, 2003.

[55] J. E. Maggs, G. J. Morales, and T. A. Carter. An Alfvén wave maser in the laboratory. *Phys. Plasmas*, 12(1):013103, 2005.

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

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

[58] 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.

[59] 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.

[60] 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.

[61] 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.

[62] 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.

[63] 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.

[64] 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.

[65] 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.

[66] 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.

[67] 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.

[68] 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.

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

[70] 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.

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

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

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

[74] Akira Hasegawa and Liu Chen. Kinetic processes in plasma heating by resonant mode conversion of Alfvén wave. *Phys. Fluids*, 19(12):1924–1934, 1976.

[75] Robert L. Lysak and William Lotko. On the kinetic dispersion relation for shear Alfvén waves. *J. Geophys. Res.*, 101(A3):5085–5094, 1996.

[76] Aaron Barnes. Collisionless damping of hydromagnetic waves. *Phys. Fluids*, 9(8):1483–1495, 1966.

[77] S. Peter Gary. The mirror and ion cyclotron anisotropy instabilities. *J. Geophys. Res.*, 97(A6):8519–8529, 1992.

[78] S. Peter Gary, Hui Li, Sean O'Rourke, and Dan Winske. Proton resonant firehose instability: Temperature anisotropy and fluctuating field constraints. *J. Geophys. Res.*, 103(A7):14567–14574, 1998.

[79] Petr Hellinger, Pavel Trávníček, Justin C. Kasper, and Alan J. Lazarus. Solar wind proton temperature anisotropy: Linear theory and WIND/SWE observations. *Geophys. Res. Lett.*, 33(9):L09101, 2006.

[80] S. D. Bale, J. C. Kasper, G. G. Howes, E. Quataert, C. Salem, and D. Sundkvist. Magnetic fluctuation power near proton temperature anisotropy instability thresholds in the solar wind. *Phys. Rev. Lett.*, 103:211101, 2009.

[81] A. A. Schekochihin, S. C. Cowley, R. M. Kulsrud, M. S. Rosin, and T. Heinemann. Nonlinear growth of firehose and mirror fluctuations in astrophysical plasmas. *Phys. Rev. Lett.*, 100:081301, 2008.

[82] C. M. Cooper, W. Gekelman, P. Pribyl, and Z. Lucky. A new large area lanthanum hexaboride plasma source. *Rev. Sci. Inst.*, 81(8):083503, 2010.

[83] 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, 2015.

[84] J.M. Finn, Z. Billey, W. Daughton, and E. Zweibel. Quasi-separatrix layer reconnection for nonlinear line-tied collisionless tearing modes. *Plasma Phys. Control. Fusion*, 56(6):064013, 2014.

[85] W. Daughton, T.K.M. Nakamura, H. Karimabadi, V. Roytershteyn, and B. Loring. Computing the reconnection rate in turbulent kinetic layers by using electron mixing to identify topology. *Phys. Plasmas*, 21(5):052307, 2014.

[86] Kevin J. Bowers, Brian J. Albright, Lin Yin, W. Daughton, Vadim Roytershteyn, B. Bergen, and T.J.T. Kwan. Advances in petascale kinetic plasma simulation with VPIC and Roadrunner. In *Journal of Physics: Conference Series*, volume 180, page 012055. IOP Publishing, 2009.

[87] N.F. Loureiro, A.A. Schekochihin, and S.C. Cowley. Instability of current sheets and formation of plasmoid chains. *Phys. Plasmas*, 14(10):100703, 2007.

[88] W. Daughton, V. Roytershteyn, B.J. Albright, H. Karimabadi, L. Yin, and Kevin J. Bowers. Transition from collisional to kinetic regimes in large-scale reconnection layers. *Phys. Rev. Lett.*, 103(6):065004, 2009.

[89] F. Jenko and B. Scott. Numerical computation of collisionless drift Alfvén turbulence. *Phys. Plasmas*, 6:2705, 1999.

[90] G.J. Morales, J.E. Maggs, A.T Burke, et al. Alfvénic turbulence associated with density and temperature filaments. *Plasma Phys. Control. Fusion*, 41:A519, 1999.

[91] A.T. Burke, J.E. Maggs, and G.J. Morales. Spontaneous fluctuations of a temperature filament in a magnetized plasma. *Phys. Rev. Lett.*, 84:1451, 2000.

[92] S. J. Zweben, C. R. Menyuk, and R. J. Taylor. Small-scale magnetic fluctuations inside the macrotor tokamak. *Phys. Rev. Lett.*, 42:1270, 1979.

[93] F. Jenko and W. Dorland. Nonlinear electromagnetic gyrokinetic simulations of tokamak plasmas. *Plasma Phys. Control. Fusion*, 43:A141, 2001.

[94] M. J. Pueschel, M. Kammerer, and F. Jenko. Gyrokinetic turbulence simulations at high plasma beta. *Phys. Plasmas*, 15:102310, 2008.

[95] M. J. Pueschel and F. Jenko. Gyrokinetic turbulence simulations at high plasma beta. *Phys. Plasmas*, 17:062307, 2010.

[96] V. Naulin. Electromagnetic transport components and sheared flows in drift-Alfvén turbulence. *Phys. Plasmas*, 10:4016, 2003.

[97] V. Naulin, A. Kendl, O. E. Garcia, A. H. Nielsen, and J. J. Rasmussen. Shear flow generation and energetics in electromagnetic turbulence. *Phys. Plasmas*, 12:052515, 2005.

[98] P.C. Liewer, J.M. McChesney, S.J. Zweben, and R.W. Gould. Temperature fluctuations and heat transport in the edge region of a tokamak. *Phys. Fluids*, 29:309, 1985.

[99] M.R. Stoneking, S.A. Hokin, S.C. Prager, G. Fiksel, H. Ji, and D.J. den Hartog. Particle transport due to magnetic fluctuations. *Phys. Rev. Lett.*, 73:549, 1994.

[100] Richard B. Horne, Richard M. Thorne, Sarah A. Glauert, Nigel P. Meredith, Dimitry Pokhotelov, and Ondřej Santolík. Electron acceleration in the Van Allen radiation belts by fast magnetosonic waves. *Geophys. Res. Lett.*, 34(17), 2007.

[101] N. N. Gorelenkov, D. Stutman, K. Tritz, L. Boozer, A .and Delgado-Aparicio, E. Fredrickson, S. Kaye, and R. White. Anomalous electron transport due to multiple high frequency beam ion driven Alfvén eigenmodes. *Nucl. Fusion*, 50(8):084012, 2010.

[102] Erwin Frederick Jaeger, Lee A. Berry, Ed F. D'Azevedo, Richard F. Barrett, S. D. Ahern, David W. Swain, Donald B. Batchelor, R. W. Harvey, J. R. Myra, D. A. D'Ippolito, et al. Simulation of high-power electromagnetic wave heating in the ITER burning plasma. *Phys. Plasmas*, 15(7):072513, 2008.

[103] Joseph V. Hollweg. Nonlinear Landau damping of Alfvén waves. *Phys. Rev. Lett.*, 27:1349–1352, 1971.

[104] A. A. Schekochihin, S. C. Cowley, W. Dorland, G. W. Hammett, G. G. Howes, E. Quataert, and T. Tatsuno. Astrophysical gyrokinetics: Kinetic and fluid turbulent cascades in magnetized weakly collisional plasmas. *Ap. J. Supplement Series*, 182(1):310, 2009.

[105] Stanislav Boldyrev, Konstantinos Horaites, Qian Xia, and Jean Carlos Perez. Toward a theory of astrophysical plasma turbulence at subproton scales. *Ap. J.*, 777(1):41, 2013.

[106] S. Vincena, W. Gekelman, and J. Maggs. Shear Alfvén waves in a magnetic beach and the roles of electron and ion damping. *Phys. Plasmas*, 8:3884, 2001.

[107] D. W. Auerbach, T. A. Carter, S. Vincena, and P. Popovich. Control of gradient-driven instabilities using shear Alfvén beat waves. *Phys. Rev. Lett.*, 105(13):135005, 2010.

[108] S. Dorfman and T.A. Carter. Nonlinear excitation of acoustic modes by large-amplitude Alfvén waves in a laboratory plasma. *Phys. Rev. Lett.*, 110(19):195001, 2013.

[109] S. Dorfman and T.A. Carter. Non-linear Alfvén wave interaction leading to resonant excitation of an acoustic mode in the laboratory. *Phys. Plasmas*, 22(5):055706, 2015.

[110] S. D. Bale, P. J. Kellogg, F. S. Mozer, T. S. Horbury, and H. Reme. Measurement of the electric fluctuation spectrum of magnetohydrodynamic turbulence. *Phys. Rev. Lett.*, 94:215002, 2005.

[111] O. Alexandrova, V. Carbone, P. Veltri, and L. Sorriso-Valvo. Small-scale energy cascade of the solar wind turbulence. *Ap. J.*, 674(2):1153, 2008.

[112] J. W. Armstrong, B. J. Rickett, and S. R. Spangler. Electron density power spectrum in the local interstellar medium. *Ap. J.*, 443:209–221, 1995.

[113] Steven A. Balbus and John F. Hawley. Instability, turbulence, and enhanced transport in accretion disks. *Rev. Mod. Phys.*, 70(1):1, 1998.

[114] Kevin D. Nielson, Gregory G. Howes, Tomoya Tatsuno, Ryusuke Numata, and William Dorland. Numerical modeling of Large Plasma Device Alfvén wave experiments using AstroGK. *Phys. Plasmas*, 17(2):022105, 2010.

[115] 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, 2012.

[116] 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. *Phys. Plasmas*, 20(7):072304, 2013.

[117] G.M. Wallace, A.E. Hubbard, P.T. Bonoli, I.C. Faust, R.W. Harvey, J.W. Hughes, B.L. LaBombard, O. Meneghini, R.R. Parker, A.E. Schmidt, et al. Lower hybrid current drive at high density in Alcator C-Mod. *Nucl. Fusion*, 51(8):083032, 2011.

[118] Philippe Jacquet, L. Colas, M-L Mayoral, G. Arnoux, V. Bobkov, M. Brix, P. Coad, D. Czarnecka, A .and Dodt, F. Durodie, et al. Heat loads on JET plasma facing components from ICRF and LH wave absorption in the SOL. *Nucl. Fusion*, 51(10):103018, 2011.

[119] Stephen J. Wukitch, B. Lipschultz, E. Marmar, Y. Lin, A. Parisot, M. Reinke, J. Rice, J. Terry, and C-Mod Team. RF plasma edge interactions and their impact on ICRF antenna performance in Alcator C-Mod. *J. Nucl. Mat.*, 363:491–497, 2007.

[120] Jon Christian Rost, Miklos Porkolab, and Réjean Louis Boivin. Edge ion heating and parametric decay during injection of ion cyclotron resonance frequency power on the Alcator C-Mod tokamak. *Phys. Plasmas*, 9(4):1262–1270, 2002.

[121] R. Ochoukov, D.G. Whyte, D. Brunner, I. Cziegler, B. LaBombard, B. Lipschultz, J. Myra, J. Terry, and S. Wukitch. Investigation of RF-enhanced plasma potentials on Alcator C-Mod. *J. Nucl. Mat.*, 438:S875–S878, 2013.

[122] D.A. D'Ippolito, J.R. Myra, R. Ochoukov, and D.G. Whyte. Modeling far-field radio-frequency sheaths in Alcator C-Mod. *Plasma Phys. Control. Fusion*, 55(8):085001, 2013.

[123] Walter Gekelman, J. Wise, P. Pribyl, R. Baker, W. Layton, J. Skrzypek, P. Niknejadi, R. Ransom, D. Lee, R. Zarinshesnas, T. Kim, R. Buck, E. Warfel, T. Tasoff, J. Carmona, S. Skolnik, L. Kim, D. Furlong, and N. Gibson. Ion acoustic wave experiments in a high school plasma physics laboratory. *Am. J. Phys.*, 75(2):103–110, 2007.

[124] W. Gekelman, P. Pribyl, J. Wise, A. Lee, R. Hwang, C. Eghtebas, J. Shin, and B. Baker. Using plasma experiments to illustrate a complex index of refraction. *Am. J. Phys.*, 79(9):894–902, 2011.

[125] Walter Gekelman. LAPTAG—a physics outreach program at UCLA. *APS News*, 11(5), 2002.