C. PROJECT DESCRIPTION

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We propose to study nonlinear and kinetic effects in large-amplitude plasma waves, focusing on parametric instability in Trivelpiece-Gould Waves (TGWs) and Electron Acoustic Waves (EAWs). The parametric instability is a fundamental nonlinear process occurring in a broad range of physical systems. In plasmas this instability has been widely investigated theoretically [58,59] and has been observed in tokamaks[60-62], high-intensity laser experiments [63,64], nonneutal plasmas [24,65] and other devices [66,67]. The parametric decay of ion acoustic waves (IAWs) has been postulated as a possible cause for the saturation of stimulated Brillouin scattering in high-intensity laser experiments [63,64,68-71]. In these experiments, the IAWs are highly kinetic with a phase velocity v_ϕ near the ion thermal speed $\overline{v}$. EAWs also have a phase velocity near $\overline{v}$, and nonlinear TGWs can be studied in this regime. Like IAWs, both TGWs and EAWs have near-acoustic linear dispersion relations.

Surprisingly, we have found that standard fluid theory analysis is inadequate to describe parametric instability for near-acoustic plasma waves. In these systems, the nonlinear coherent structures (cnoidal waves and solitons) represent a balance between the (fluid) nonlinearity and dispersion; but we find that the stability of these structures depends critically on particle *kinetics*. We propose experiments and kinetic theory to elucidate the instability mechanisms.

In preliminary theory work we have uncovered a novel kinetic parametric instability process associated with charged particles trapped in the potential wells of the electrostatic waves. The instability mechanism, described below in Sec. 3, is quite simple and general, and could be of importance in other waves with trapped particles such as EAWs, and laser-driven IAWs. It is known that trapped particles can modify the parametric instability in IAWs, but the mechanisms are obscure and there can be several instability processes happening at once [72]. Our system has only a single plasma species with waves travelling in only one dimension (along the plasma column), making a theoretical description easier and making experimental results simpler to interpret.

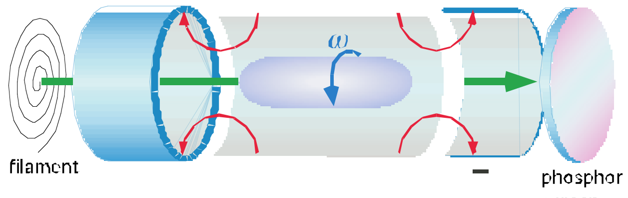
Experiments to test the theory of this process will be carried out on the pure electron and pure ion plasma devices at UCSD. Both devices are well-developed mature experimental systems, each with an array of diagnostic capabilities that allow accurate measurement of mode frequencies, amplitudes, growth and decay rates, as well as detailed velocity distribution functions of importance in kinetic processes. The experimental set-ups are described below in Sec. 2. Specific TGW and EAW experiments and theory development are proposed in Sec. 3. Broader impacts of the proposed research program are considered in Sec. 4, and results from prior NSF/DOE grants are discussed in Sec. 5.

The following table shows current senior group personnel.

Senior Personnel	Project Scientists
• Prof. Daniel H.E. Dubin, PI	Dr. Francois Anderegg
• Prof. C. Fred Driscoll, co-PI	Dr. Andrey Kabantsev
• Prof. Thomas M. O'Neil, co-PI	

2a. CamV: Camera-diagnosed electron plasmas

The CamV apparatus is a Malmberg-Penning trap designed to study the dynamics of pure electron plasmas.



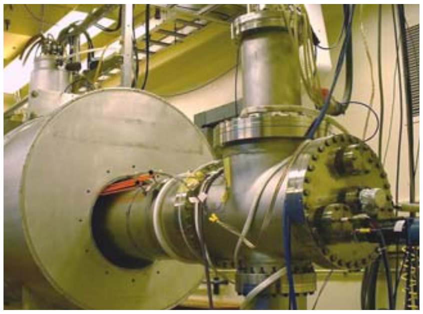


Fig. 1. CamV cutaway schematic; and apparatus.

The unneutralized electron plasma is trapped in a series of 15 cylindrical electrodes in an ultra-high vacuum environment (Fig. 1). The electrons are contained axially by negative voltages on two end cylinders, and confined radially by a uniform axial magnetic field ($B_z \leq$ 2 Tesla), resulting in a confinement time of about 100 sec. The trapped electron column typically has density $n \sim 10^7$ cm^{-3}, radius $R_p \sim 1.5$ cm, and axial length $L_p \sim$ 50 cm, with controlled temperatures in the range $0.03\text{eV} \lesssim T \lesssim 3\text{eV}$. Individual electrons bounce rapidly axially with low collisionality $\nu_{\perp\parallel} \approx 10-10^3\ \text{sec}^{-1}$, and $\mathbf{E}\times\mathbf{B}$ drift across the magnetic field.

Electron plasma waves can be excited reproducibly through controlled application of time-oscillating potentials to one or more confinement electrodes. The waves are diagnosed by measuring wave-induced image currents running to and from grounded electrodes, and by wave-phase-coherent measurement of the density eigenfunction $\delta n(r,\theta,z,t)$.

The z-integrated electron density $n(r,\theta,t)$ can be measured (destructively) by dumping the electrons axially onto a phosphor screen, which is imaged by a low-noise CCD camera. For $k_z = 0$ waves the 3D density $n(r,\theta,z,t)$ and self-consistent potential $\phi(r,\theta,z,t)$ are constructed for each image by assuming a Boltzmann equilibrium along each field line. The z-averaged velocity distribution function $f(r,\theta,z,v_z,t)$ can be reconstructed from partial dumps over controlled electrostatic barriers. For a $k_z = 1$ wave, the plasma can be cut in half before the dump, so that the z-average is only over half-the wave length and therefore does not average to zero [73]. The shot-to-shot variations in the initial profiles are small, so a time evolution can be obtained from a sequence of shots with differing hold times. CamV incorporates about 7 racks of control and diagnostics electronics, as well as an extensive set of custom software programs, enabling fully quantitative measurements of wave and transport effects.

Subtle kinetic effects have been previously measured on CamV, including collisional dissipation at separatrices induced by localized particle trapping in electric and magnetic wells. Plasma eigenmodes have been reconstructed using the aforementioned dump method, and the velocity distribution function in the presence of a wave has been reconstructed[74]. This has led to improved understanding of the kinetic theory of several important plasma processes including:

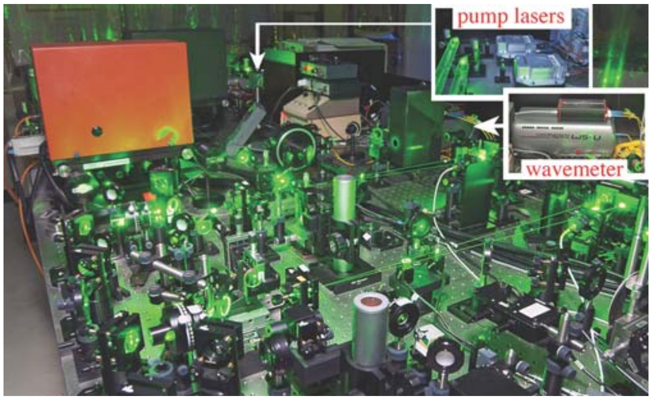
*Chaotic Neoclassical Transport in the parametric decay of drift waves[24]
*Separatrix-induced damping of diocotron waves[25,75] and θ-asymmetric BGK plasma waves [76]
—Superbanana particle transport in the low-collisionality regime [23, 25, 77-79]

2b. IV: Laser-diagnosed ion plasmas

The IV apparatus contains unneutralized Mg$^+$ ions rather than electrons, so that sophisticated Laser-Induced Fluorescence techniques can be used for diagnostics and control. The Mg$^+$ ion plasmas have density $n = 10^6 - 10^8\,\text{cm}^{-3}$, radii $R_p = 0.5 - 1.$ cm, and lengths $L_p = 1 - 30$ cm, with thermal energies ranging over $T = 10^{-5} - 10^0$ eV, in a magnetic field $B \leq 3$ Tesla.

The ions are confined in steady-state for days or even weeks using the “rotating wall” technique [36,80-84], allowing measurements with unprecedented control and precision. This technique has now been adopted by 27 institutions world-wide [85-102], including the anti-matter recombination experiments at CERN [103-107]. By varying temperature over 5 decades and density over 2 decades, the IV experiments provide strong tests of theory in many plasma regimes.

LIF diagnostic techniques allow time- and space-resolved measurement of density, temperature and rotation velocity, as well as measurement of the full velocity distribution function; moreover, “test” particles can be “spin-tagged” and followed in time. The laser system can also be used to cool or heat the plasma or to manipulate the radial profile. Figure 3 shows the laser table: two tuneable CW dye lasers that are pumped by two solid state 10W 532 nm lasers. The dye lasers at 560 nm are frequency-doubled with two custom frequency-doubling cavities, producing two 10mW beams at ~280nm, which can be directed either along or across the plasma column.



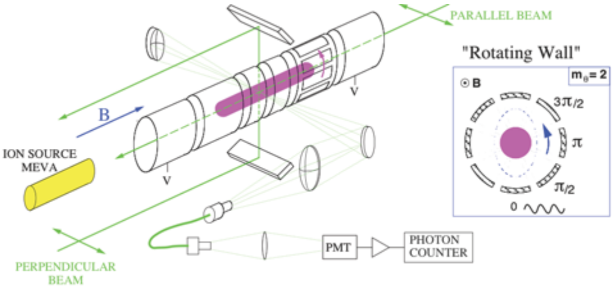


Fig. 2. Dual 280 nm CW lasers for manipulation and measurement; and schematic of the IV apparatus.

Recent improvements in laser frequency control and stability allow plasma cooling and velocity diagnostics down to velocities of order 1 m/s. The control and diagnostics electronics incorporates 9 racks of equipment and many special-purpose processes.

Plasma waves are excited using the same techniques as for CamV. They are measured nondestructively through wave-induced image currents on the surrounding electrodes, and through wave-phase-coherent LIF analysis, giving density and velocity eigenfunctions of the waves. For electron acoustic waves wave-phase-coherent imaging has been used to observe predicted nonlinear flattening of the distribution function and phase change of the plasma response at the wave phase speed [108].

Since inception, the IV apparatus has enabled quantitative comparison to theory on a broad range of basic plasma effects. The asterisks denote the first (or only) measurements of a specific effect.

—Ion Cyclotron modes in multi-species plasmas. We use these modes to obtain detailed information on ion species invisible to the laser diagnostics [3, 8-10,126]
—Thermally-excited Langmuir modes. Measured thermal electrostatic fluctuations provide a separate method of determining plasma temperature. [109]
* Rotating Wall ∞-time confinement. Using an applied rotating electric field allows effectively infinite plasma confinement times (days – weeks). [80,81,83]
* Salpeter Enhancement of Close Collisions. The first detailed measurement of the enhancement of nuclear reaction rates in a strongly-coupled plasma, using cyclotron energy as an analog for nuclear energy [17,21,110,111]
* Diffusion from Long-Range Collisions. Enhanced cross-magnetic field like-particle diffusion was measured (and predicted) from collisions with impact parameters not included in the classical (Braginskii) coefficients [112,113]
—Linear Landau damping & Trapping oscillations in TGWs. [114]
* Heat Transport from Long Range Collisions. Two Order-of-magnitude enhancement of cross-magnetic field heat transport was measured (and predicted) from collisions with impact parameters not included in the classical (Braginskii) coefficients [115]
* Electron Acoustic Waves. First measurement of the “thumb diagram” dispersion relation, and nonlinear modifications to the velocity distribution function [108]
* Shear Reduction of collisional transport, observation of Dawson-Okuda transport. In a strong-magnetic field cross-field collisional diffusion scales as B^{-1} and is reduced by applied rotational shear [116]

* Verification of enhanced collisional drag from long-range collisions, as measured through drag-damping of TGWs [20]

—Bounce-harmonic Landau damping of TG waves [15]

3. Parametric Decay of Near-Acoustic Nonlinear Waves

In the parametric decay process a large amplitude wave (the "pump wave") decays to two "daughter" waves with longer wavelength, which grow exponentially and sap energy from the pump. This fundamental nonlinear process is observed in waves on a range of scales in a great many physical systems, and has consequently been studied both theoretically and experimentally for decades. The process is particularly important in laser-plasma interaction experiments. A fluid-based theory of the instability process was laid out in classic work by Galeev, Sagdeev and co-workers [58].

In preliminary work described below (Sec. 3a), we have applied this theory to experiments on the parametric decay of standing TG modes to longer wavelength, e.g. axial wavenumber $k_z = 2(\pi / L)$ decaying to $k_z = 1(\pi / L)$. Of particular interest here is that for a finite radius plasma column, TG waves have near-acoustic dispersion for small k_z, enabling a near-resonant 3-wave decay from a large amplitude k_z = 2 mode to k_z = 1 modes via $(\omega_2 = \omega_1 + \omega_1\ ,\ k_2 = k_1 + k_1)$. This process is an example of the type considered in the 3-wave theory of Galeev and Sagdeev.

Several aspects of the preliminary experiments were described by the 3-wave fluid theory, but several important aspects were not. At low pump amplitude the theory predicts that the daughter waves oscillate in amplitude rather than grow exponentially, at a frequency ω_B close to the "detuning" $\Delta\omega = 2\omega_1 - \omega_2$ between the pump and daughter waves. This was observed. Also, at larger pump amplitudes exceeding a threshold, the daughter waves were observed to grow exponentially, as predicted in the 3-wave theory.

However, in 3-wave theory this amplitude threshold depends linearly on $|\Delta\omega|$. On the other hand, the experiments observed strong temperature dependence to both the threshold and the parametric decay rate (see below), which cannot be explained by the 3-wave theory. The experiments also observed that for a range of intermediate amplitudes below the threshold for exponential growth, the daughter waves grew, but not exponentially. Instead the amplitude slowly oscillated, and the size of the oscillations grew. This behavior is also not described by 3-wave theory.

Furthermore, the 3-wave theory keeps only the pump and daughter waves, each described by a single frequency and wavenumber. But for a near-acoustic dispersion relation, many *harmonics* of the pump and daughter waves are also near resonance (eg. $\omega_4 = \omega_2 + \omega_2\ ,\ k_4 = k_2 + k_2$). Experiments can observe these harmonics in signals picked up by the wall electrodes. Consequently a more general fluid treatment of the decay that includes the harmonics, termed M-wave theory, was developed ([11], Sec. 3a below). However, this presumably superior theory predicted that the harmonics exert a stabilizing influence and found that *for a periodic travelling wavetrain (cnoidal wave) there is no parametric instability, for any wave amplitude*. The theory also analyzed nonlinear standing waves, and found weak instability with growth rates far smaller than observed experimentally. Moreover, the predicted threshold amplitudes for onset were several times the observed thresholds.

We now believe that the resolution to these discrepancies between theory and experiment lies in a new *kinetic* theory of the parametric decay. In the (preliminary) theory, the decay process is not driven by nonlinear fluid coupling between modes as in the fluid theory. Instead, the instability is driven by the destabilizing influence of charged particles trapped in the wave troughs. In the instability, adjacent peaks of the wave-train approach one-another (and therefore recede from the next peaks). This modulation in the wave train adiabatically heats particles trapped between the approaching peaks, and cools trapped particles between receding peaks. This heating and cooling would normally produce pressure and potential restoring forces that stabilize the motion of the peaks. However, some trapped particles gain enough energy to become untrapped, and these particles are then retrapped and cooled between receding peaks. The net effect of this detrapping and retrapping is to *change the sign of the restoring force*, producing a trapped particle pressure and potential that *amplifies* the modulation.

This simple and general parametric decay mechanism may explain the discrepancies between the standard fluid theory and our past experiments on nonlinear waves, and could also apply to other plasma systems displaying parametric decay, such as EAWs and IAWs.

Below, we discuss the different theories for the parametric instability in somewhat more detail, and discuss preliminary and proposed experiments and simulations that test the new kinetic theory of the instability. We also propose extensions of the theory and experiments to EAWs, which also exhibit parametric decay.

a) Fluid theory of Nonlinear TGWs.

In the cold fluid theory of Trivelpiece-Gould waves, plasma density $n(r,z,t)$, fluid velocity $\mathrm{V}(r,z,t)$ and potential $\phi(r,z,t)$ are coupled through continuity, momentum, and Poisson equations. Linearization of the equations (assuming small-amplitude waves) yields a near-acoustic dispersion relation for TGW's given by

$$\omega = \frac{\omega_p k_z}{\sqrt{k_z^2 + k_\perp^2}} \tag{1}$$

where ω_p is the plasma frequency, and $k_\perp$ is the wavenumber of the modes perpendicular to the magnetic field, given by $k_\perp = \sqrt{2/\log(r_w/r_p)}$, where r_p is the column radius and r_w is the radius of the wall electrodes. For $k_z / k_\perp \ll 1$ this dispersion relation is near-acoustic, with $\omega \sim (\omega_p / k_\perp)k_z$.

In the standard 3-wave theory of nonlinear parametric instability, one *assumes* a large-amplitude pump wave with a single parallel wavenumber k_2 and single frequency component ω_2 , related by the linear dispersion relation (a nonlinear frequency shift is sometimes added as an ad-hoc correction). This pump wave couples through the nonlinear (convective derivative) terms in the continuity and momentum equations to longer-wavelength daughter waves, each with a single wavenumber component k_1 and frequency ω_1 .

Energy is transferred from the pump to the daughter waves via this nonlinear coupling. When a resonance condition is met (which can be expressed as an amplitude threshold; see below), the energy transfer causes unstable growth of the daughter waves, which saps energy from the pump wave, causing parametric decay of the pump wave.

A two-timescale analysis can be carried out to derive the growth rate of the daughter waves, assuming that the energy transfer rate is slow compared to the wave frequencies; this turns out to require that the frequency detuning $\Delta\omega \equiv 2\omega_1 - \omega_2$ is small,

$$\Delta\omega << \omega_1$$

and that the pump wave amplitude A is small,

$$A << 1.$$

Here the pump wave density perturbation $\delta n_2(r,z,t)$ is related to A through $\delta n_2 / n_0 = A\exp(i(k_2 z - \omega_2 t)) + \text{c.c.}$. The analysis shows that the daughter waves grow at a rate Γ that depends on the pump wave amplitude and frequency detuning through the expression

$$\Gamma = \frac{1}{2}\sqrt{\left(3A\omega_1\right)^2 - \Delta\omega^2} \ . \tag{2}$$

Thus, the 3-wave theory predicts that there is a parametric decay instability when the pump amplitude satisfies the instability threshold

$$A > \frac{|\Delta\omega|}{3\omega_1}. \tag{3}$$

For pump waves with amplitudes below this threshold, the growth rate given by Eq. (2) is imaginary, which means that the daughter waves do not grow exponentially, but instead oscillate in amplitude.

The results quoted above are for travelling waves, but nearly identical results are obtained in the three-wave theory of standing waves. [11]

M wave fluid theory

For a near-linear dispersion relation such as the TG wave relation, Eq. (3) is inconsistent with the assumption that pump and daughter waves consist of single wavenumbers and frequencies [11]. If the amplitude A of a TG wave is large enough to satisfy Eq. (3), then it is large enough to produce several time and space harmonics in both the pump and daughter waves, and these harmonics greatly modify the instability growth rate, obviating Eq. (2). This M-wave fluid theory (where M is the number of Fourier modes kept in the description of the waves) shows that for travelling waves the daughter waves are not exponentially unstable; rather, they only oscillate in amplitude, no matter how large the pump amplitude. Moreover, the oscillation frequency ω_B of the daughter wave amplitudes, shown in Fig. 3, only matches three wave theory (the dashed line) for very low amplitudes. For larger amplitudes, mode coupling to $M>2$ Fourier modes becomes important and many such modes must be kept to obtain converged results.

An extension of the M-wave theory describing standing waves rather than travelling waves was also developed [11]. Here a weak parametric instability was found to occur, but the amplitude threshold was several times that observed in the experiments, and the growth rates were several times smaller than observations.

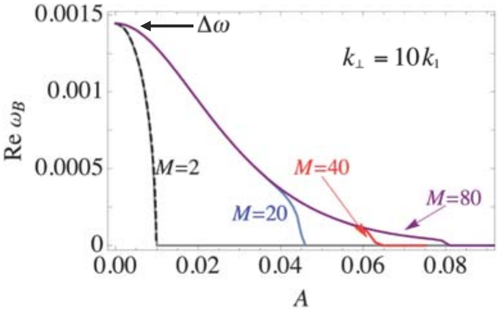


Fig. 3.. Oscillation frequency ω_B of the daughter wave amplitudes on a travelling TGW of amplitude A, as the number of modes M kept in the wave description increases. 3 wave theory, Eq. (2), corresponds to the M=2 curve. [11]

b) New (Proposed) Trapped Particle Kinetic Theory of TGW parametric decay

In our experiments on cold plasmas, the phase velocity $v_\phi = \omega / k_z$ of a TG wave may be up to 10-100 times the thermal speed. Kinetic effects associated with trapped particles are therefore *not* important in low-amplitude TG waves in cold plasmas. However, for large wave amplitudes, this is not true; particle trapping can occur. For $\bar{v} \ll v_\phi$ the requirement for particle trapping is roughly

$$v_\phi \lesssim \sqrt{2\Delta\phi / m},$$

where $\Delta\phi = \phi_{\max} - \phi_{\min}$ is the depth of the potential wells in the wave. When $\Delta\phi$ approaches $m v_\phi^2 / 2$, the width of the cats eyes (phase-space separatrices) associated with the wave is sufficiently large to trap particles. A typical phase space plot for the particle distribution function in such a wave is displayed in Fig. 4, in the moving frame of the wave where the wave potential is stationary. In this frame plasma flows through the wave with mean velocity $-v_\phi$, but some particles are trapped in the wave's cats eyes. This is so even though the wave speed in this example is 9.3 times the thermal speed of the distribution. More particles would be trapped if the plasma were hotter. Note that the particle distribution function $f(E)$ depends on particle position and velocity only through the energy E as seen in the frame of the wave,

$$E = \frac{1}{2} m v_z^2 + \phi(z), \qquad (4)$$

where $v_z = v_{z\,lab} - v_\phi$ is the particle velocity in the wave frame, $\phi(z)$ is the wave potential, and the potential is determined self-consistently from the Poisson equation (we suppress radial dependence of the TGWs to simplify the discussion). Thus, the nonlinear TGW is a type of BGK state [117] with no Landau-damping. The wave can still damp through collisional drag[20] or viscosity[118] but there are easily-accessible density and temperature regimes where these effects are slower than parametric instability.

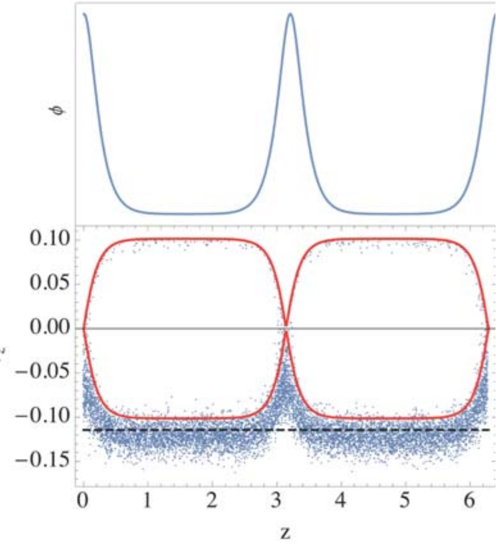


Fig. 4. Potential $\phi(z)$ (upper plot) and particle positions in phase space (lower) in the wave frame. Red curve: separatrix. Dashed line: mean particle velocity $-v_\phi$ as seen in the wave frame.

Note also that most of the trapped particles have energies close to the separatrix energy $E = \phi_{\max}$ (given by the red curve in Fig. 4). This is important in understanding the instability mechanism.

The new kinetic instability mechanism depends on these trapped particles. In the parametric instability, the wave peaks move relative to one-another, ultimately merging so that a k_z=2 wave becomes a k_z=1 wave. When particles trapped in the wave potential are bouncing between the potential peaks, they can gain or lose energy as these peaks move with respect to one-another. To illustrate this, Fig. 5 displays two energy bands of trapped particles. As the distance between adjacent peaks slowly increases, trapped particles lose energy through adiabatic cooling; likewise, particles trapped between approaching peaks gain energy adiabatically. A group of deeply-trapped particles (the blue band of particles in Fig 5) will therefore provide a restoring force to the peak motion, which *stabilizes* the parametric instability. For instance, for the particles in the left blue band that are being compressed, their kinetic energy and density increase (Fig. 5b), creating a thermal pressure and potential that pushes back on the two approaching peaks.

However, for particles weakly-trapped near the separatrix energy, the *opposite effect* occurs. Consider the red band of particles in Figs. 5. As particles between approaching peaks are heated through compression they gain enough energy to exceed $\phi_{\max}$ and detrap. The density and pressure of the compressed trapped particles then *decreases*, because there are *fewer* of them after compression (Fig .5b). The detrapped particles immediately retrap between the next pair of receding peaks, and so the density and pressure of this set of particles *increases* as the number of these trapped particles increases. The pressure and potential from these particles amplifies the motion of the peaks, driving the instability.

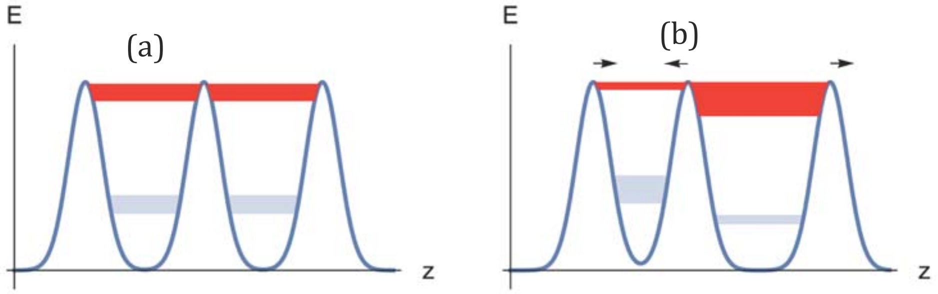


Fig 5a: Two energy bands of particles trapped in the potential wells of a large amplitude wave. Blue: deeply-trapped. (i.e. at low energy) Red: weakly-trapped (i.e. near the separatrix energy). Fig 5b. Response of the two bands to compression and expansion from relative motion of the wave peaks (arrows) in the parametric instability.

Note that in a cold plasma wave there are more particles trapped weakly, near the separatrix energy, than are deeply trapped (see Fig. 4 for example), so the net effect of the trapped particles is to destabilize the wave. A preliminary theory of this effect implies that, for cold plasmas, the parametric instability growth rate of the daughter waves is

$$\Gamma = \sqrt{\alpha^2 f_{tr} - \omega_B^2}\,, \tag{5}$$

where f_{tr} is the fraction of trapped particles, $0<f_{tr}<1$, ω_B is the cold-fluid oscillation frequency of the daughter waves, shown in Fig. 3, and α is a coefficient (with units of frequency) that depends on pump wave amplitude A, $k_\perp / k_1$, and the functional form of the trapped particle distribution function. When there are no trapped particles (f_{tr}=0), Eq. (5) implies that there is no growth, and instead there are amplitude oscillations at frequency ω_B , as expected in cold fluid theory. Note that since ω_B is small for large amplitude waves (as per Fig. 3), the fraction f_{tr} of trapped particles required for instability can be quite small.

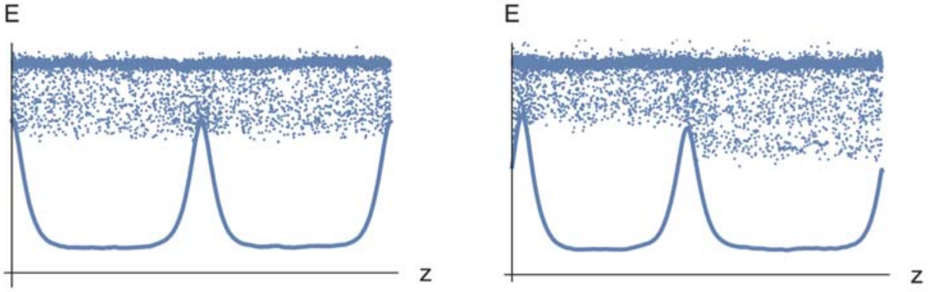


Fig.. 6a: Initial phase-space particle positions in the (E-z) plane (dots) and wave potential (curve) in a PIC simulation of parametric decay. A small fraction f = 0.0004 of particles is trapped in the wave potential. Fig 6b: As the wave peaks move, particles are expelled from the left well and retrapped in the right well, resulting in more particles in the right well than in the left. This produces a pressure and potential that amplifies the peak motion.

Fig. 6. displays preliminary particle-in-cell (PIC) simulations (with periodic boundary conditions in z) that show the instability of a large amplitude TG travelling wave with A=0.078 and with $k_\perp = 10k_1$. The initial particle distribution consists of 10^6 particles at nearly zero temperature, (i.e. all have almost the same energy E) distributed in position self-consistently so as to produce the wave potential; and a weak tail of 2000 particles distributed in energy

down into the potential wells of the wave. This distribution is somewhat artificial, but is chosen because the effect of the instability is easy to see.

At later times, as the peaks move slowly relative to one-another in the instability (Fig. 6b), trapped particles are expelled from the potential well between approaching peaks, and collect in the well between receding peaks. The resulting trapped particle pressure and potential amplifies the motion of the peaks, causing the parametric instability. The exponential growth rate Γ can be observed in these simulations by measuring the change $\Delta z(t)$ in relative position of the wave peaks as a function of time, as shown in Fig. 7, and fitting to an exponential.

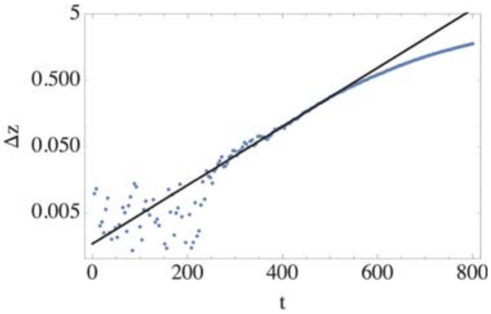


Fig. 7. Exponential growth in the change in relative position of the wave peaks (plotted on a log scale). Black line is a fit of the form $a\exp(\Gamma t)$.

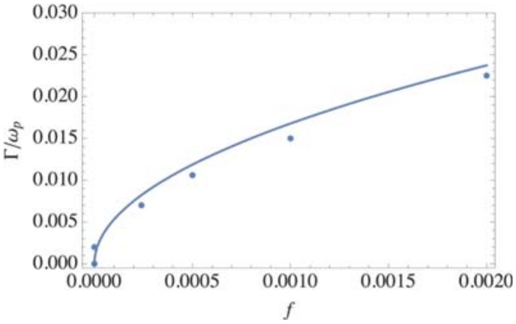


Fig. 8 Growth rate from Eq. (5) (curve) compared to PIC simulation results (dots), as trapped particle fraction f_{tr} is varied. Here $k_\perp = 10k_1$, $A = 0.078$

By varying the number of particles in the tail of the distribution from zero up to a few thousand, growth rates versus the trapped particle fraction are obtained as shown in Fig 8. The curve is Eq. (5), using a preliminary theory estimate for the parameter α for this wave, and ω_B is taken from the fluid theory decribed by Fig. 3 .

Even small trapped particle fractions can drive the wave unstable because ω_B is small for these large amplitude TGWs. Physically, this means that without trapped particles, these large amplitude waves have almost no restoring force with respect to relative motion of the peaks. In other words, they are nearly a set of evenly-spaced non-interacting solitons. Only a very small fraction of trapped particles is necessary to overcome the weak restoring force through the above-described mechanism.

The new kinetic theory for the parametric instability is promising: Eq. (5) exhibits an amplitude threshold for instability as well as temperature dependence, as seen in the experiments. For small amplitudes, ω_B is larger (Fig. 3) and the fraction f_{tr} of trapped particles in a cold plasma is small because the separatrix is far from the particle distribution. For larger amplitudes, ω_B decreases and f_{tr} increases until the instability threshold is reached. The threshold and the growth rate depend on temperature: as T increases at fixed wave amplitude A, f_{tr} increases, lowering the instability threshold and increasing the growth rate. This is qualitatively what is observed in the experiments (see below).

We propose to make a careful comparison between a fully fleshed-out version of the new kinetic theory, simulations, and experiments. For a direct comparison to experiments we will also extend the theory to understand trapped particle effects on nonlinear standing waves. This will be challenging since the cats-eyes that determine particle trapping exhibit complex time variation on a timescale of order the wave period, as opposed to the much slower evolution of the cats-eyes in the wave frame of travelling waves. Simulations will provide guidance to theory in this case. Preliminary simulation work shows that trapped particles still produce a destabilizing effect similar in magnitude to that seen in traveling waves, but this is not yet fully understood theoretically.

c) Preliminary and Proposed Experiments on Nonlinear TGWs

In the preliminary experiments [13], standing $k_z = 2$ TG waves were excited on a finite length plasma column by oscillating the potential applied to a cylindrical confinement electrode. The amplitude of these $k_z = 2$ waves was controlled by varying the amplitude of the applied voltage, and the number of voltage oscillations. Typically a burst of 40 wave cycles was applied. The bursts were ramped to/from full amplitude over four cycles to minimize excitation of other waves. However, this procedure also heated the plasma somewhat.

Fig. 9 shows three types of amplitude evolution observed in the experiments:

a) For large pump amplitude, parametric decay of k_z=2 accompanied by exponential growth of k_z=1 daughter waves (in this case at rate $\Gamma = 4570\ \mathrm{s}^{-1}$);

b) For intermediate pump amplitude, slow average growth (at mean rate $\langle\Gamma\rangle = 420\ \mathrm{s}^{-1}$ in this case) of the daughter waves accompanied by amplitude oscillations;

c) For small pump amplitude: oscillations of the daughter wave amplitude of magnitude A_B, at rate $\omega_B \sim \Delta\omega$.

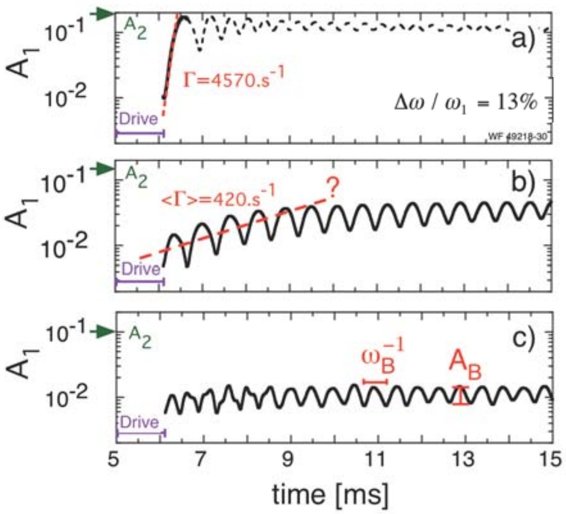


Fig. 9 Experimental observation of nonlinear interactions between k_z =2 pump wave , anmplitude A_2, and k_z = 1 daughter waves with amplitude A_1. (a) A_2 = 0.2 (b) A_2=0.15 (c) A_2 = 0.1

Also, the pump amplitude required for onset of exponentially-growing waves decreased as plasma temperature increased (Fig 10). At the largest temperatures the onset was less than three-wave theory would predict. The data clearly shows that the growth rate is larger at larger temperature. This behavior cannot be explained by the standard fluid analysis of parametric instability.

In simulations of the instability, we also observe slow average growth of the daughter waves accompanied by amplitude oscillations, at intermediate amplitudes of the pump, and *the effect is again related to the trapped particles*. We observe the k_z=2 wave is not initially unstable; pump wave peaks oscillate around their equilibrium positions in the wave; but in each oscillation more trapped particles are created due to chaos in the region of the separatrix, induced by what appear to be secondary instabilities in the particle distribution function. As f_{tr} increases slowly with time, the amplitude of the oscillations increases. This behavior is more complex to model analytically than pure exponential growth since a model of the chaotic increase in trapped particles is required, but it may be related to conservation of wave action in the daughter waves as f_{tr} increases.

Also, weak heating of the plasma caused by the pump wave excitation makes it difficult to determine exactly what the initial trapped particle fraction is in the experiments. We believe that this is why there is little difference in the growth rate between a plasma with an initial $v_\phi \sim 30\overline{v}$ and one with $v_\phi \sim 5\overline{v}$: it is likely that the $v_\phi \sim 30\overline{v}$ plasma is heated by the wave excitation, creating a weak tail of relatively high energy particles that is being trapped in the wave. This is an open question that we will address in future experiments. We will use a different "gentler" excitation method that does not cause as much heating.

We also have the ability to measure the distribution function in order to determine the trapped particle distribution, using the laser-diagnostics of the IV machine. We have measured the distribution for BGK states previously [108] using this method, and propose to apply it to the TGWs so that we may fully understand the effect trapped particles have on the parametric decay instability. We estimate that the current laser setup will be able to distinguish trapped particle fractions above the photon counting noise floor of less than 1%. Here, the received LIF photons are phase-binned coherently with N cycles of a received wave, revealing the phase-coherent dynamics while

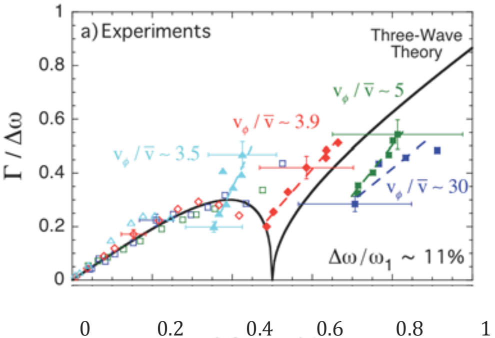


Fig. 10. Daughter-wave amplitude oscillation rate at low amplitude (open circles) and exponential growth rate at larger amplitude (solid symbols) for four different thermal speeds. Sold line, three-wave theory.

reducing noise by $\sqrt{N}$. The preliminary theory predicts that a smaller amplitude wave than shown in Fig. 6, with larger ω_B, will require trapped particle fractions of this magnitude to be driven unstable. Technical modifications (see the budget justification) should allow even lower trapped particle populations to be measured.

d) Proposed Theory and Experiments on Parametric Decay in EAWs

Experiments at UCSD were the first to experimentally map out the full dispersion relation for EAWs [108,119]. Parametric decay in EAWs has also been observed in our experiments [120] and in related simulations [121]. We propose to study this process in theory and in further experiments. The decay process has several interesting features and differences compared to parametric decay of TGWs.

For small amplitudes, EAWs also have a near-acoustic dispersion relation given by

$$\omega = \sqrt{2}\,\zeta\,\overline{\mathrm{v}}\,k_z\,, \tag{6}$$

where the parameter ζ is a weak function of k_z obtained by solution of the equation

$$(k_z^2 + k_\perp^2)\lambda_D^2 = -(1+\zeta\,Z(\zeta)), \tag{7}$$

and where λ_D is the Debye length, and $Z(\zeta)$ is the Principal part of the plasma dispersion function [122]. For $k_z \ll k_\perp$, Eq. (7) shows that ζ is nearly independent of k_z (the k_z term on the lhs of Eq. (7) can be dropped), and then Eq. (6) shows that ω is proportional to k_z (acoustic dispersion).

Eq. (7) actually provides the dispersion relation for both TGWs and EAWs, as there are two roots to the equation. The root with lower ζ falls in the range $0.92<\zeta<1.5$, and describes EAWs. Thus, EAWs have a phase velocity that is near the thermal speed. For instance, in the experiments a typical value of $k_\perp\lambda_D$ is 0.3, which when used in Eq. (7) implies $\zeta = 1.01$ when $k_z \ll k_\perp$; and so $\omega \sim 1.4 k_z\overline{\mathrm{v}}$ when $k_z \ll k_\perp$.

Because EAWs have low phase velocities, they would normally be strongly Landau-damped. But they are a nonlinear BGK state [117,168] that has flattened the distribution function for the particle speeds that are near the phase velocity of the wave, through particle trapping. Thus, EAWs are nonlinear even at small amplitude, and are fundamentally kinetic in nature. Because of this latter fact, standard fluid theory of parametric decay cannot be directly applied to the parametric decay of EAWs.

Equations (6) and (7) apply only to small-amplitude EAWs. For larger amplitudes, we have observed that the flattening of the distribution function that accompanies the formation process of the EAW can significantly impact the frequency of the waves. In experiments with a given k_z, larger amplitude EAWs could be set up over a range of frequencies [119]. This frequency malleability is quite different than TGWs, and has important effects on the parametric decay process. A larger amplitude k_z =2 EAW with frequency ω_2 can drive resonant k_z = 1 daughter waves with little or no detuning, i.e $\omega_1 = \omega_2 / 2$, since the frequency of the daughter waves is variable, depending on the driving.

We are in the process of developing a generalization of 3-wave theory for EAWs. Accounting for the fundamentally kinetic nature of these waves requires a theory that goes beyond the standard fluid approach. The theory is also complicated by the fact that, for these waves with $\mathrm{v}_\phi / \overline{\mathrm{v}} \sim 1$, there is always a significant amount of particle trapping. The previously-described kinetic instability mechanism driven by trapped particles may then also play a significant role in EAW parametric decay. However, the distribution of trapped particles is typically rather flat, with as many deeply trapped particles as weakly-trapped particles near the separatrix energy. We believe this could significantly lower the impact of the trapped particles on instability growth rates, and may even cause them to be stabilizing; but this is an open question that will be pursued in future theory, simulations, and experiments.

4. Broader Impacts of the Proposed Research

From a scientific perspective, parametric decay is a fundamental nonlinear process that is of interest in many disciplines. The proposed kinetic trapped-particle instability mechanism is simple and should be generally applicable to a broad range of nonlinear plasma waves. We believe the work will have a particularly important impact in the laser-plasma interactions community, and may therefore also impact laser-driven fusion energy research. The quest for cleaner forms of energy, such as fusion energy, is an important societal goal.

From a societal perspective, the PIs give strong emphasis to the teaching and outreach aspects of their research. The UCSD plasma group is committed to equality of opportunity in the scientific enterprise. Our research has an important educational component, both in terms of training future scientific leaders and in terms of educational outreach to communities that are traditionally underrepresented at UCSD. Over the 3 year period of the grant we intend to graduate at least two Ph.Ds and train at least one postdoc. Members of the group periodically give general science lectures at local public schools in order to foster interest in science and plasma physics. Group members also participate in several summer and weekend programs that expose underrepresented students to campus scientific activities by bringing groups of such students to campus to participate in skill-building and basic science experiments. We intend to continue to support these important outreach aspects of our scientific effort.

5. Results from Prior NSF/DOE Support

NSF/DOE grants in the past 5 years

Agency	Award #	Project Title	Dates	Award
NSF	PHY1414570	Fundamental Processes in Plasmas	7/14-7/17	900K
DOE	DESC0002451	Fundamental Processes in Plasmas	7/14-7/17	1.2M
HEDLP	DESC0008693	Experiments and Theory on Nonlinear Waves and the Salpeter Screening Enhancement	8/15-8/18	650K
NSF	PHY1707271	Fundamental Processes in Plasmas	7/17-7/20	15K
DOE	DESC0018236	Fundamental Processes in Plasmas	7/17-7/20	1.2M
DOE	DESC0016532	2D Vortex Dynamics in Externally Imposed Flows Studied Using Electron Plasmas (Surko, PI)	8/16-7/19	500K

In the past five years our group has received grants from the NSF/DOE partnership for basic plasma physics research, but the funding was decreased in the last review cycle due to budget cuts at the agencies, as shown in the Table. Awards are total amounts allotted over three years. We have also previously obtained funds from the DOE HEDLP initiative for research into strongly-coupled plasma physics and nonlinear waves, but this funding is not being renewed for programmatic reasons. Past NSF/DOE and DOE HEDLP grants funded our preliminary work on nonlinear TGWs and EAWs as described in the previous sections. The present proposal will enable theory and experiments to continue in this research area.

Dubin has also provided theory support to the Surko group on a DOE grant on 2D vortex dynamics. However, it is important to note that both our current NSF/DOE grant, "Fundamental Processes in Plasmas" running to July 2020, and the Surko DOE grant, have no overlap in scope with that of the proposed research in this document.

Intellectual Merit

The long-term collaboration between Dubin, Driscoll, and O'Neil has developed theory and experiment on a wide range of fundamental processes in plasmas. The conceptual simplicity, long confinement times, and excellent control of cylindrical non-neutral plasmas has enabled incisive quantitative comparison of theory and experiment in a range of areas. The high quality of the research has been recognized through many invited and plenary session lectures and through several major APS awards (1991 Dawson Award, 1996 Maxwell Prize, 2000 Dawson Award).

In the following paragraphs we briefly describe some research highlights from the past five year period (not including the previously-described work on nonlinear waves).

Cyclotron Waves, Bernstein Modes

We developed theory [6] and experiments [3,8,9,10] characterizing cyclotron mode frequency shifts in multi-species ion plasmas, due to external E-fields and collective plasma effects. Measurement of the frequency shifts allows a *non-destructive high-accuracy* determination of the mass and *concentration* of each plasma species. We also developed the method of Thermal Cyclotron Spectroscopy (TCS) [9], which provides faster and more accurate species concentration measurements, down to the 0.1% range. This work comprised a portion of the Ph.D. thesis of M. Affolter.

Our group has also recently developed a kinetic theory and an accompanying numerical analysis [6] for linear electrostatic waves near the cyclotron frequency $f_c^{(s)}$ of any given species s. Building on prior analyses [123-126], the theory and numerics keep non-uniform radial density, finite cyclotron radius corrections and non-Maxwellian distribution corrections. The results describe surface cyclotron waves varying as $\exp(im\theta)$, and also predict coupling of these waves to radially and axially propagating finite-temperature Bernstein waves [127-129] near the cyclotron frequency. These Bernstein waves produce a new set of normal modes in the plasma column as they propagate radially between center and edge.

Damping of TGWs

Our proposed work on parametric decay of nonlinear TGWs was preceded by several years of effort to understand various other aspects of these waves. Wave damping mechanisms received particularly careful study in the previous reporting period.

(1) Enhanced Bounce-Harmonic Landau Damping of TGWs

We have studied the enhanced "bounce-harmonic" Landau-damping of long-wavelength small-amplitude Trivelpiece-Gould (TG) oscillations, caused by potential variations along the plasma column [4,7,12,15]. This damping mechanism dominates over other processes at temperatures somewhat below the regime of normal Landau damping (Fig. 11).

Landau damping arises from resonant interactions between a traveling wave with axial phase velocity $v_\phi = 2\pi f / k_z$ and nominally free-streaming charges with velocities near v_ϕ. For standing TG waves on a finite-length plasma column, hypothesizing "specular reflection" at the ends preserves the Landau resonance at $f = f_B(E)$ for particles with energy $E = m v_z^2 / 2$ bouncing end-to-end at frequency $f_B = v_z / 2L$. The Landau damping predicted from this resonance is the red curve in Fig. 11.

However, introducing realistic z-dependent end potentials, or other potential variations along the column, causes particles to speed up and slow down rather than simply reflect from the ends. This introduces extra Fourier time-harmonics in the particle trajectory relative to the wave phase, causing "bounce-harmonic" Landau-damping from particles satisfying $f_B(E) = f / n$ for integer n [130,131].

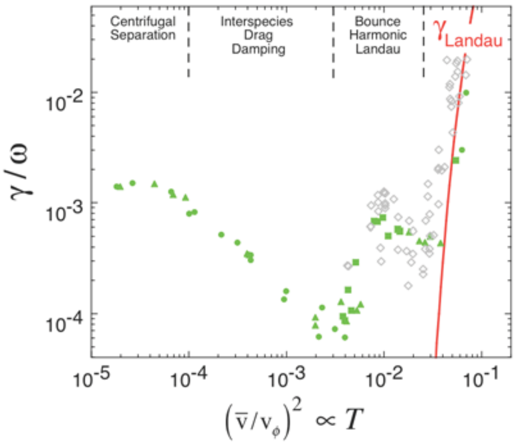


Fig. 11 . Damping of plasma waves in electron (open circles) and ion (solid circles) plasmas spanning four decades in temperature T and four physical regimes.

Our recent theory work analyzed these bounce-harmonic effects in detail [4,7,12], motivated by the "bigger-than-Landau" damping measurements displayed in Fig.11 for $0.003 < (\bar{v} / v_\phi)^2 < 0.03$. Although bounce-harmonic Landau damping has been inferred from previous observations in mirror machines [132,133], our recent experiments [15] have provided a precise, direct test of the bounce-harmonic Landau damping theory. The theory and experiments comprised a portion of the Ph. D. theses of A. Ashourvan and M. Affolter respectively.

(2) Drag-Damping of TGWs

Our experiments [20] have measured the damping rate of small-amplitude TGWs in a multi-species ion plasma, testing a new theory of collisional slowing (see below). Over a range of about 2 decades in temperature (Fig. 11), the damping is dominated by collisional drag between the plasma species. Heavy species react to the wave electric field less than light species, and the difference in parallel velocities induces a frictional drag between species that damps the wave. For plasmas that are both radially uniform and have weak collisionality $(\nu_{ss'} \ll \omega_{TG})$, the collisional drag damping rate γ can be solved analytically as [134]

$$\gamma = \frac{1}{4\omega_p^2} \sum_s \sum_{s'} \frac{(M_s - M_{s'})^2}{M_{s'}^2} \omega_{p,s}^2 \nu_{ss'},$$

where $\omega_{p,s}^2 = 4\pi e^2 n_{0s} / M_s$ is the species s plasma frequency squared, and $\omega_p^2 = \sum_s \omega_{p,s}^2$ is the total plasma frequency squared. More generally, the damping rate is determined by numerically-solving the coupled linearized fluid and Poisson equations for the mode potential, including drag between species.

Figure 12 shows our first measurements of TG mode damping rates in the temperature regime where drag damping dominates, compared to two theories: the classical (Braginskii) theory found in standard plasma textbooks (dashed lines) and a new theory (solid lines) described below [19], that keeps effects from "long-range collisions" neglected in the classical theory that are important in plasmas in strong magnetic fields. Note that in the experiments, compositions are accurately measured using the TCS method described above. In all three plasmas shown, the observed damping agrees with the new theory keeping long-range collisions, with no adjustable parameters.

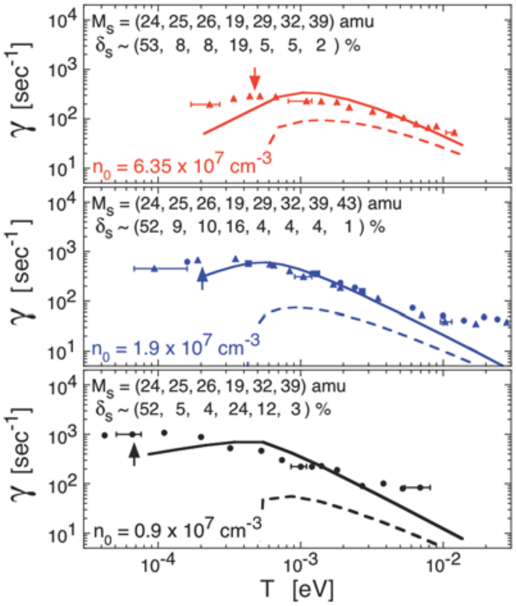


Fig. 12. Drag damping rates for three plasmas with different densities and compositions. Symbols are measurements and curves are theory for classical collisions (dashed) or including long-range collisions (solid). [19]

Long Range Collisions

In the past reporting period, our research on transport has focused on the parallel slowing rate $\nu_{ss'}$ due to collisional drag between species s and s'. This rate is important to a number of processes, including the growth rate of non-ideal plasma instabilities, magnetic reconnection, and runaway electrons[143-145]; however, a precise theory of the rate had not been previously formulated for plasmas in the regime $r_c < \lambda_D$. Our new theory[19] and experiments (Fig. 12)[20] show that the collisional slowing rate can be considerably enhanced over classical (Braginskii) theory. Enhanced transport arises from long-range collisions, in which particles interact when separated by impact parameters ρ in the range $r_c < \rho < \lambda_D$.

Previous work in our group established that classical theory [135-138] also grossly underestimates cross-field diffusion, heat transport, and viscosity, when the relevant cyclotron radii are small compared to the Debye length (i.e. $r_c << \lambda_D$).

In short-range "classical" collisions, the particle velocity vector scatters, shifting the particle guiding center by $\Delta r \approx r_c$; such scattering occurs only for small impact parameter $\rho \lesssim r_c$. Experiments with neutral plasmas have investigated this classical transport in various regimes [139-142]. Long-range collisions have impact parameter $\rho > r_c$; for these collisions, the interaction electric field causes the particles to **E** × **B** drift across the magnetic field, and also to exchange parallel energy and momentum. The transport resulting from these long-range collisions can be orders of magnitude larger than classical transport; for example, long-range cross-magnetic-field heat transport is *independent* of magnetic field. Note that this enhanced transport is due to collisions and thermal fluctuations, not to turbulence. Although the experiments are performed on non-neutral plasmas, the implications of the theory extend to plasmas in general.

Transport from External Field Errors

Over the past 3 decades our group has studied neoclassical transport (NCT) processes in plasmas. These enhanced collisional transport processes are caused by external electric and magnetic field asymmetries. NCT is important in fusion plasmas but is often masked by turbulent transport. In our nonneutral plasma system there is no plasma turbulence, and by applying asymmetries in a controlled manner we can isolate these NCT processes from other transport effects.

We have observed that dissipation at separatrices between trapped and passing particles often dominates the NCT, particularly when the plasma is weakly collisional with $\nu \ll \omega_r$, where ω_r is the plasma rotation frequency. This separatrix dissipation is a form of "superbanana transport", a regime of NCT of importance in modern stellarator design. Our theory and experimental efforts have characterized a new "chaotic" plateau regime of superbanana transport that occurs when the separatrix is asymmetrical ("ruffled"), causing *collisionless* particle orbits to trap and de-trap chaotically[22-25,77-79]. Then the collisional separatrix boundary layer is superceded by a collisionless layer caused by this chaotic scattering across the ruffled separatrix.

Salpeter Collisional Enhancement from Correlations

We performed experiments [21,41,46,110,111] on the Salpeter enhancement of reaction rates due to interparticle correlations. These experiments represent the *only* quantitative laboratory tests of the Salpeter enhancement, which is incorporated into all models of stellar nucleosynthesis. The experiments build on a mathematical isomorphism developed by Dubin, relating fusion collisions in dense, degenerate, astrophysical matter, such as the interior of a white dwarf, to perp-to-parallel collisions in strongly magnetized ion plasmas [146-148].

Our experiments have demonstrated rate enhancements of several orders of magnitude in the strongly correlated regime, growing with coupling parameter Γ as exp(Γ) for $\Gamma > 1$. Our recent experiments [21] have measured the enhancement for $\Gamma < 1$ and have laid to rest a controversy over the possibility of "dynamical screening" in the collisions[149-152]. This work was chosen for the subject of a recent AIP SciLight article [http://aip.scitation.org/doi/full/10.1063/1.5006423].

Flux-Driven Damping of Diocotron Waves

We have recently discovered [26,28,29,30,31] a new variant of spatial Landau damping of $\exp(im\theta)$ diocotron modes, equivalent to surface waves on 2D vortices [153-157]. The damping occurs when some external process drives a *flux* of particles (i.e. vorticity) through the wave/rotation resonance (critical) layer R_{cm}, defined by $\omega = m\, f_E(R_{cm})$. The damping is unusual in that it is *algebraic* in time rather than exponential. This offers possible explanation for the widely observed rapid symmetrization of vortices: even weak viscosity (which cannot directly dissipate the wave-induced shear) may actually cause symmetrization by *driving* vorticity through the resonance layer. The CamV experiment provides quantitative density measurements, allowing accurate calculation of wave-frame potential and critical radius.

2D Vortex Stripping

While isolated 2D vortices tend toward axisymmetry [158,159] (through spatial Landau damping) they can be deformed and/or destroyed by external shear or strain flows. Experiments in viscous fluids such as water, and simulations, have shown that a strained vortex may undergo partial or total destruction as the vorticity is pulled away in thin filaments [160,161] (vortex stripping), but a quantitative understanding of many aspects of these processes is incomplete.

In cooperation with the Surko experimental group, Dubin has studied the relatively simple case of the 2D dynamics when a pure strain flow is *rapidly* applied to an initially axisymmetric, isolated vortex in an inviscid fluid[32]. The strain velocity field is $\mathrm{v}_s = \varepsilon(x\hat{y} + y\hat{x})$ where 2ε is the strain rate, and the vorticity is $\omega = \nabla \times \mathrm{v}$ with v the fluid velocity. The dependence of vortex dynamics on the magnitude of ε and on the initial radial vorticity profile was investigated.

Experiments were done using a magnetized pure electron plasma to model an incompressible inviscid 2D fluid [162], and strain applied via a sectored wall electrode. An advantage of this system is that electron density, which is analogous to fluid vorticity, can be measured directly. Complementary Vortex-In-Cell simulations (Fig.13) were conducted to validate the 2D nature of the experimental results and to extend the parameter range of the studies[159].

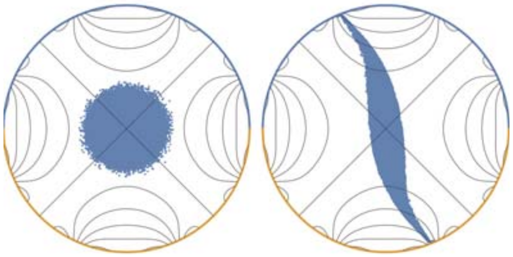


Fig. 13. Simulation of electron density (vorticity) at two times in an initially-cylindrical electron plasma column (left) to which a strain field is applied using wall sectors. Curves are contours of applied strain potential.

A comparison of the results to a simple elliptical patch model (Kida [163]) shows good agreement for small strain fields where the vortex ellipticity oscillates in the applied strain; but for larger strains discrepancies appear as the vortex is stripped. More detailed theory and simulations indicate that the fraction of vorticity lost to the wall depends sensitively on the magnitude of the strain and also on the initial radial vorticity profile; this is also observed in the experiments[32].

2D Ion Crystals Confined to the $z = 0$ Plane

In work motivated by discussions with NIST Boulder researchers on quantum entanglement and q-bit implementations, Dubin was able to solve analytically [27] for the planar density per unit area $\sigma(r)$ for a single-species cold plasma confined in the z=0 plane in a Penning or Paul trap by an arbitrary external trap potential, expressed as a multipole expansion. For a Penning trap with up to M applied multipoles, Dubin found an exact finite series solution for the equilibrium plasma areal density versus radius, $\sigma(r)=\sqrt{1-r^2/R_p^2}\sum_{n=0}^{M/2-1}\sigma_{2n}r^{2n}$, where the plasma radius R_p and the coefficients σ_{2n} are determined analytically in terms of the applied multipole strengths and the number of trapped ions. Using this solution for the density, the combination of low-order multipoles that produces the most uniform planar plasma crystal with fewest defects can be determined. In simulations, the defects in ion crystals confined in these multipole traps were found to be isolated to the circular edges of the crystal, allowing a large defect-free uniform central region that would be more useful for many AMO studies than non-uniform crystals contained in current quadrupolar trap designs, where the M=2 multipole is dominant. These mutipole configurations are being used in current AMO experiments [164].

Review and Tutorial Papers

As part of the UCSD plasma group commitment to education, Anderegg and Dubin participated in several Les Houches Winter Schools, resulting in tutorial papers on basic plasma physics [37-39] and fundamental aspects of nonneutral plasmas [33,34,36]. Dubin also helped prepare a major review on the scientific applications of trapped positrons [35].

b) Broader Impacts of prior NSF/DOE support

Our past graduate students have been diverse in gender, culture, and ethnicity. The 31 graduates from this group over the past two decades have gone on to successful careers in science and industry; and some have themselves become educators, training students in their own right. In the past five years we have graduated three Ph.Ds and trained two postdocs. Undergraduate students are excited by and learn from laboratory and simulation projects through department honors projects and internships; several have co-authored journal articles. The PIs have integrated their research into innovative undergraduate classes: Dubin developed a new undergraduate mathematical physics course and textbook; Driscoll has taught an independent-projects-based course focused on embedded microprocessors. Driscoll, Dubin and O'Neil have all been DPP Distinguished Lecturers, traveling to small colleges and minority colleges. Dubin and Anderegg have lectured on basic plasma physics to international graduate students at Les Houches Winter Schools [33,34,36-39], Dubin and O'Neil have co-authored several review articles of interest to the broader scientific community, [34,165-167] and Dubin and Anderegg have served the APS Division of Plasma Physics in several leadership positions, including Secretary/Treasurer and the Program Committee.

Our plasma research has been rich in connections to the wider world of physics. Our pure electron plasma experiments model the 2D ideal flow of neutral fluids, and we have made definitive measurements of Kelvin wave dynamics, 2D vortex merger, and the inviscid decay of 2D turbulence. Surprisingly, the turbulent decay can result in a “vortex crystal”, intriguingly similar to vortex crystals observed in superconductors and superfluids. Our theoretical and experimental work on trapped ion plasmas has strong connections to the atomic physics, time-standards, and ion crystal work at NIST Boulder, as was recognized through a shared Excellence Prize for Dubin and Bollinger. The magnetically confined pure ion plasmas and crystals are a simple laboratory realization of the OCP model of dense, degenerate astrophysical matter such as the interior of a white dwarf. The experimental demonstration of correlation- enhanced close collisions models the long-predicted Salpeter enhancement of fusion rates in dense, degenerate astrophysical matter. The groups at CERN that have successfully produced and trapped anti- hydrogen credit our group for the development of useful techniques to confine, control, and diagnose their anti-proton and positron plasmas. Our theoretical studies of “guiding center drift atoms” and three-body recombination also support the anti-hydrogen projects. Although much of our work advances basic plasma, the work on neoclassical transport tests and advances fusion-relevant physics. We intend to continue making such interdisciplinary connections during the renewal period.

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165. D.H.E. Dubin and T. M. O’Neil, “Trapped Nonneutral Plasmas, Liquids and Crystals (the Thermal Equilibrium States)”, Rev. Mod. Phys. **71**, 87 (1999)
166. D.H.E. Dubin, “Plasma Collisional Transport”, in *Long-Range Interacting Systems* (T. Dauxois, S. Ruffo and L. Cugliandolo, editors), Oxford Univ. Press (2009), pp. 381-438.
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DANIEL H.E. DUBIN, Principal Investigator

(a) Professional Preparation

Queen's University, Kingston Canada	Theoretical Physics	B.Sc., 1978
Princeton University, Princeton NJ	Plasma Physics	MA, 1981
Princeton University, Princeton NJ	Astrophysics	Ph.D., 1984
Univ. of Calif., San Diego CA	Postgrad Research Physicist	1984-1987

(b) Appointments

7/00 - present	University of California, San Diego - Professor
7/94 - 6/00	University of California, San Diego - Associate Professor
7/87 - 6/94	University of California, San Diego - Assistant Professor

(c) Products

(i) 5 most closely related to the proposed project:

1. D.H.E. Dubin, A. Ashourvan, "Nonlinear Trivelpiece-Gould Waves: Frequency, Functional Form and Stability" Physics of Plasmas **22**, 102201 (2015)
2. F. Anderegg, C.F. Driscoll, D.H.E. Dubin, and T.M. O'Neil "Wave-Particle Interactions in Electron Acoustic Waves in Pure Ion Plasmas," Phys. Rev. Lett. **102**, 095001 (2009).
3. F. Anderegg, C.F. Driscoll, D.H.E. Dubin, T.M. O'Neil and F. Valentini "Electron Acoustic Waves in Pure Ion Plasmas," Phys. Plasmas **16**, 055705 (2009)
4. F. Valentini, T.M. O'Neil and D.H.E. Dubin "Excitation of nonlinear electron acoustic waves," Phys. Plasmas **13**, 052303:1-7 (2006)
5. F. Anderegg, M. Affolter, A. Ashourvan, D.H.E. Dubin, F. Valentini and C.F. Driscoll "Non-Linear Plasma Wave Decay to Longer Wavelength," AIP Conf. Proc **1668**, 020001 (2015).

(ii) 5 other significant products:

1. D.H.E. Dubin and T.M. O'Neil, "Trapped Nonneutral Plasmas, Liquids and Crystals (The Thermal Equilibrium States), Rev. Mod. Phys. **71**, 87 (1999).
2. T.B. Mitchell, J.J. Bollinger, D.H.E. Dubin, X.-P. Huang, W.M. Itano, and R.H. Baughman, "Direct Observations of Structural Phase Transitions in Planar Crystallized Ion Plasmas," Science 282, 1290 (1998).
3. D.H.E. Dubin, "Theory of Electrostatic Fluid Modes in a Cold Spheroidal Nonneutral Plasma," Phys. Rev. Lett. **66**, 2076 (1991).
4. D.H.E. Dubin and T.M. O'Neil, "Cross-Magnetic-Field Heat Conduction in Nonneutral Plasmas," Phys. Rev. Lett. **78**, 3868 (1997).
5. D.H.E. Dubin, J. Krommes, C. Oberman and W. Lee, "Nonlinear Gyrokinetic Equations," Phys. Fluids **26**, 3524 (1983).

(d) Synergistic Activities

- APS Excellence in Plasma Physics Award (2000);
- Secretary-Treasurer of APS/DPP (2013—2016);
- APS/DPP Distinguished Lecturer (2012—2014);
- APS/DPP Executive Committee (2007—2010);
- DAMOP Allis Prize Committee (2009, 2010).
- **Total Number of Graduate Students:** 7

C. FRED DRISCOLL, Co-PI

(a) Professional Preparation

Cornell University, Ithaca NY	Physics (Summa Cum Laude)	B.A., 1969
Univ. of California, San Diego CA	Physics	M.S., 1971
Univ. of California, San Diego CA	Physics	Ph.D., 1976

(b) Appointments

July 2012 - Present	Research Professor, UCSD Physics
July 1996–2012	Professor, UCSD Physics
Dec 1991-2009	Associate Director, Institute for Pure and Applied Sciences at UCSD
Sept 1976–June 1996	Research Physicist/Sr. Lecturer, UCSD Physics Department

(c) Selected Products

(i) Products closely related to proposed project

1. M. Affolter, F. Anderegg, D.H.E. Dubin, C.F. Driscoll, “First Test of Long-Range Collisional Drag via Plasma Wave Damping”, Phys. Rev. Lett. **117**, 155001 (2016).
2. F. Anderegg, M.Afolter, A.A. Kabantsev, D.H. Dubin, A.Ashourvan, C.F. Driscoll, "Bounce Harmonic Landau Damping of Plasma Waves", Phys. Plasma **23**, 055706 (2016).
3. F. Anderegg, M. Affolter, A. Ashourvan, D.H.E. Dubin, F. Valentini and C.F. Driscoll "Non-Linear Plasma Wave Decay to Longer Wavelength," AIP Conf. Proc **1668**, 020001 (2015).
4. F. Anderegg, C.F. Driscoll, D.H.E. Dubin and T.M. O'Neil "Electron Acoustic Waves in Pure Ion Plasmas," AIP Conf. Proc. **1114**, pp. 89-95 (2009).
5. A.A. Kabantsev, F. Valentini and C.F. Driscoll "Experimental Investigation of Electron-Acoustic Waves in Electron Plasmas," Non-Neutral Plasma Physics VI (edited by M. Drewsen et al.), AIP Conf. Proc. **862**, pp. 13-18 (2006)

(ii) 5 other significant products:

6. A.A. Kabantsev, C.Y. Chim, T.M. O'Neil, and C.F. Driscoll "Diocotron and Kelvin Mode Damping from a Flux through the Critical Layer", Phys. Rev. Lett. **112**, 115003, 2014.
7. A.A. Kabantsev, Yu.A. Tsidulko and C.F. Driscoll "Chaotic Neoclassical Separatrix Dissipation in Parametric Drift-Wave Decay", Phys. Rev. Lett. **112**, 055003, 2014.
8. F. Anderegg, D.H.E. Dubin, T.M. O’Neil and C.F. Driscoll, “Measurement of Correlation-Enhanced Collision Rates,” Phys. Rev. Lett. **102**, 185001 (2009).
9. C.F. Driscoll, F. Anderegg, D.H.E. Dubin, D.-Z. Jin, J.M. Kriesel, E.M. Hollmann, and T.M. O'Neil, “Shear Reduction of Collisional Transport: Experiments and Theory,” Phys. Plasmas B **9**, 1905 (2002).
10. F. Anderegg, E.M. Hollmann, and C.F. Driscoll, “Rotating Field Confinement of Pure Electron Plasmas Using Trivelpiece-Gould Modes,” Phys. Rev. Lett. **81**, 4875 (1998).

(d) Synergistic Activities

- Mentor for REU and NUF summer students, including APS/DPP participation; 3-yr mentorship of physics/math student with disability (A.Shelley)
- APS Excellence in Plasma Physics Research Award (1991);
- APS/DPP Executive Committee (1995-98); Program Committee (1996-97); Sundry APS Excellence Prize Committees;
- APS/DPP Distinguished Lecturer in Plasma Physics (1999-2000); UCSD Revelle Teacher of the Year (2001);
- Chair of NNP-2001 Workshop; obtained NSF funding for student participation;**Total**
- **Number of Graduate Students: 14**

THOMAS M. O’NEIL, Co-PI

(a) Professional Preparation

California State College, Long Beach CA	Physics	B.S., 1962
Univ. of California, San Diego CA	Physics	M.S., 1964
Univ. of California, San Diego CA	Physics	Ph.D., 1965

(b) Appointments

1967 - present UCSD Physics: Assistant, Associate, Full Professor, Distinguished Research Professor
1965 - 1967 General Atomics—Research Staff

(c) Products

(i) 5 most closely related to the proposed project:

1. F. Anderegg, C.F. Driscoll, D.H.E. Dubin and T.M. O’Neil, “Wave-Particle Interactions in Electron Acoustic Waves in Pure Ion Plasmas,” Phys. Rev. Lett. **102**, 095001 (2009).
2. F. Valentini, D. Perrone, F. Califano, F. Pegoraro, P. Veltri, P.J. Morrison and T.M. O’Neil, “Undamped Electrostatic Plasma Waves,” Phys. Plasmas **19**, 092103 (2012).
3. C.Y. Chim and T.M. O'Neil, "A Mechanistic Interpretation of the Resonant Wave-Particle Interaction", Physics of Plasmas, **23**, 050801 (2016).
4. C.Y. Chim and T.M. O'Neil, Flux-driven Algebraic Damping of m=1 Diocotron Mode", Physics of Plasmas, **23,** 072113 (2016).
5. A.A. Kabantsev, C.Y. Chim, T.M. O'Neil, and C.F. Driscoll "Diocotron and Kelvin Mode Damping from a Flux through the Critical Layer," Phys. Rev. Lett. **112**, 115003, 2014.

ii) other significant products:

1. D.H.E. Dubin and T.M. O’Neil, “Trapped Nonneutral Plasmas, Liquids and Crystals (The Thermal Equilibrium States), Rev. Mod. Phys. **71**, 87 (1999).
2. M.E. Glinsky, T.M. O’Neil, M.N. Rosenbluth, K. Tsuruta, and S. Ichimaru, “Collisional Equipartition Rate for a Magnetized Pure Electron Plasma,” Phys. Fluids B **4**, 1156 (1992).
3. J.H. Malmberg and T.M. O’Neil, “The Pure Electron Plasma, Liquid and Crystal,” Phys. Rev. Lett. **39**, 1333 (1977).
4. T.M. O’Neil and R.W. Gould, “Temporal and Spatial Plasma Wave Echoes,” Phys. Fluids **11**, 134 (1968).
5. T.M. O’Neil, “Collisionless Damping of Nonlinear Plasma Oscillations,” Phys. Fluids **8**, 2255 (1965).

(d) Synergistic Activities

- National Research Council Plasma Science Committee (Member, 1997-03; Chair 2000-03); Member, National Research Council Board on Physics and Astronomy (2003-04);
- Chair, UCSD Physics Department (1998-2001);
- APS/DPP Distinguished Lecturer in Plasma Physics (1997-1998); Distinguished Teaching Award from UCSD Alumni Association (1996)
- APS James Clerk Maxwell Prize (1996); APS Excellence in Plasma Physics Research Award (1991)
- Science Advisory Board for Tri Alpha Energy (current)

Total number of graduate students: 12