White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 19 2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
• Interactions of plasmas and waves	P
• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Plasma Waves on Non-Maxwellian Particle Velocity Distributions
Corresponding Author:	Francois Anderegg
• Institution:	UCSD
• email:	fanderegg@ucsd.edu
Co-Authors:	T.M. O'Neil, D.H.E. Dubin, A. Kabantsev, C.F. Driscoll

- ***Describe the research frontier* and importance of the scientific challenge.**

Novel kinetic waves have recently been predicted by theory and observed experimentally on plasma with slightly non-Maxwellian particle velocity distributions. An entire new class of waves has recently been identified in plasmas with velocity distributions flattened at v_{phase}, allowing waves with a given wave number to propagate at a range of frequencies. Experiments suggest that velocity distributions spontaneously evolve to make the plasma resonant with a range of driver frequencies. Understanding the plasma response to drive frequencies is of broad interest.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Iterated comparisons of theory and simulation with well controlled experiment is required.
The particles velocity distribution can be tailored with lasers or with antenna. Experiments have indicated that an initially off resonance driver can modify the distribution until the driver becomes resonant with a new wave. Further techniques to control the distribution function will be developed.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Understanding these new waves may be the key to tame stubborn plasma instabilities in plasmas exposed to intense drivers.
Also this type of research is ideal to train graduate students in university research groups with strong theory and experiment program.

Plasma Waves on Non-Maxwellian Particles Velocity Distributions

Following the pioneering studies of Berstein, Green and Kruskal (BGK) [1] an enormous theoretical literature [2] argued that nonlinear wave states can exist with wave number and frequency well off the usual linear dispersion curves. However, the theory suggested that these nonlinear waves require carefully tailored trapped distributions and it was not clear that the waves could be easily excited by drivers in real experiments.

Recent experiments (and simulations) have shown that such off dispersion waves are easily excited and ring robustly. By off dispersion, we mean off the usual dispersion predicted for a Maxwellian velocity distribution. At least for simple cases, the off dispersion waves satisfy the dispersion curve for a slightly altered Maxwellian, that is a Maxwellian with a small flat plateau created by nonlinearly trapping at the wave phase velocity. The plateau is created when a resonant drive is applied over many trapping periods. One expects that these off dispersion waves can be excited in many plasmas with intense drivers.

Trapped non-neutral plasmas have been useful systems to excite and study these off dispersion waves. New experimental techniques provide some control of the particle velocity distribution using external antenna and tailored rf bursts, resonant interaction with a laser beam can also modified the particle velocity distribution function. Wave coherent laser induced fluorescence techniques allow direct measurement of the particle distribution in the presence of the wave.

"Small flat spots" on Maxwellian distributions are created by driving the plasma with an external field at a given frequency and wave number. These slightly modified Maxwellian have led to the experimental observation of **E**lectron **A**coustic **W**aves. EAWs are the low frequency branch of electrostatic plasma (Langmuir) waves. The EAW typically has a phase velocity $v_{ph} \sim 1.4\bar{v}$, quite low compared to typical plasma waves, and its frequency has a strong temperature dependence, $f_{EAW} \propto T^{1/2}$. Linear Landau damping would suggest that such slow phase velocity waves are strongly damped; but at finite wave amplitudes, trapping of particles near the phase velocity "flattens" the distribution function, resulting in a weakly damped wave. These waves have been studied theoretically [3] and numerically [4]; they have been observed in experiments with non-neutral plasmas [5] and in laser-produced plasmas [6]. Figure 1 (from ref.5) shows a phase-coherent measurement of $f(v)$ for a standing wave in trapped ion plasmas. Note that the plateau located at the phase velocity oscillates with the wave phase from positive to negative velocity.
The EAW name is also applied to substantially different waves on bi-Maxwellian distributions in space physics [7].

While studying on dispersion EAW's, experiments discovered that waves can be excited and ring robustly well off the linear dispersion curve for a Maxwellian. When a relatively intense driver field with wave number and frequency off the linear dispersion curves is applied for many trapping periods, a plateau is created around the driver phase velocity and a new mode, with only slightly shifted frequency, rings after the driver is turned off.

A theoretical explanation for this remarkable property is that the corners of the plateau formed by the drivers make a large contribution to the perturbed charge density for the wave. The sign and magnitude of this corner charge density is very sensitive to the wave phase velocity, so only a slight shift in phase velocity (or frequency, for fix wavenumber) can create a new mode, called a corner mode, at frequency and wave number where none existed on the Maxwellian plasma.

Figure 2 (from ref.8) shows part of the particle distribution with a flat spot. The dashed line shows the drive phase velocity and the dotted dashed line indicates the phase velocity of the excited wave. An on dispersion mode rings essentially at the same frequency as its driver, in contrast an off (Maxwellian) dispersion mode rings at a lower frequency. [8]

"Extreme distortion" of a Maxwellian velocity distribution can routinely be created by frequency chirped drive. Plasma wave excited on these distributions are easily excited to large amplitude and have extremely low damping. Figure 3 shows the measured particle velocity in a pure ion plasma before and after a frequency chirped drive [9]. Also shown on figure 3 is the wave amplitude at various locations along an electron plasma column showing strong non-sinusoidal behavior [10].

Summary

EAW types of waves have been observed in laser fusion and on bi-Maxwellian distributions in space physics. In both cases diagnostics are extremely challenging. In contrast measurement on trapped non-neutral plasma have measured the wave coherent velocity distribution function, and have found waves existing off Maxwellian distributions when $f(v)$ is tailored with an external drive.

Understanding these waves on non-Maxwellian velocity distributions may be important to tame unwanted plasma instability in hot plasma exposed to intense drivers. Well-diagnosed low collisionality non-neutral plasmas are ideally suited to investigate these new types of waves on non-Maxwellian velocity distributions.

Furthermore these detailed theory-experiment comparisons offer unique training for graduate students. Training new Ph.D. in plasma physics is essential to replenish the aging plasma physicist population.

References

[1] I. B. Bernstein, J. M. Greene, and M. D. Kruskal, Phys. Rev. **108**, 546, (1957)

[2] For comprehensive review of the nonlinear dynamical development, including trapping and saturation, with discussion of parallel discoveries in fluid mechanics and other disciplines, see, N. J. Balmforth, P. J. Morrison, and J.-L. Thiffeault, Rev. Mod. Phys., commissioned (2013).arXiv:1303.0065v1[cond-mat.stat-mech] 1 Mar 2013

[3] J. P. Holloway and J. J. Dorning, Phys. Rev. A **44,** 3856 (1991).

[4] F. Valentini, T.M. O'Neil and D.H.E. Dubin, Phys. Plasmas **13**, 052303:1-7 (2006).

[5] F. Anderegg, C.F. Driscoll, D.H.E. Dubin, and T.M. O'Neil, Phys. Rev. Lett. **102**, 095001 (2009).

[6] D. S. Montgomery, R. J. Focia, H. A. Rose, D. A. Russell, J. A. Cobble,J. C. Fernndez, and R. P. Johnson, Phys. Rev. Lett. **87**, 155001, 2001

[7] S. P. Gary and R. L. Tokar, Phys. Fluids, **28**, 2439 (1985)

[8] F. Valentini, D. Perrone, F. Califano, F. Pegoraro, P. Veltri, P.J. Morrison, and T.M. O'Neil, Phys. Plasmas **19**, 092103 (2012)

[9] F. Anderegg, C.F. Driscoll, D.H.E. Dubin, T.M. O'Neil and F. Valentini, Phys. Plasmas **16**, 055705 (2009)

[10] W. Bertsche, J. Fajans and L. Friedland, Phys. Rev. Lett., **91**: 265003, 2003.

Figures

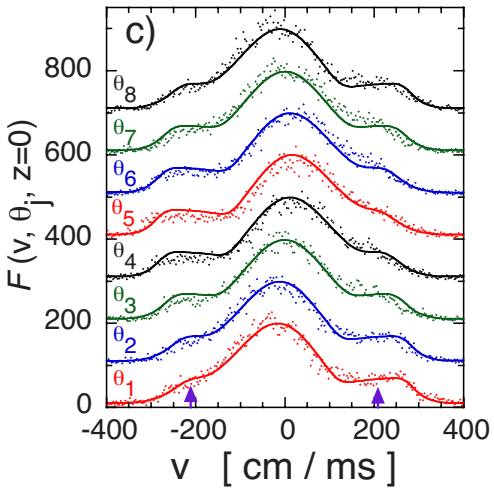

Figure 1 *Phase coherent particle velocity distribution in the presence of an EAW [5].*

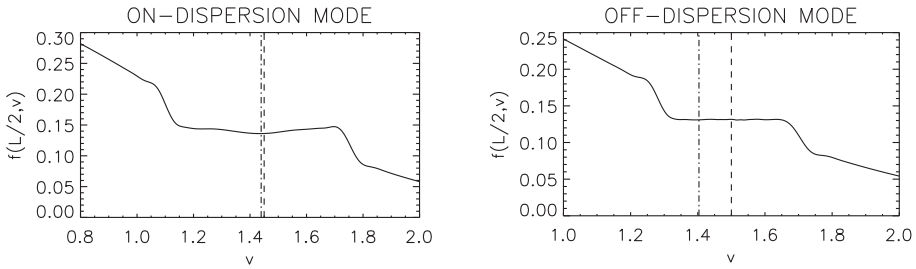

Figure 2 *Off-Maxwellian dispersion modes have a phase velocity different than the one setup by the drive [8].*

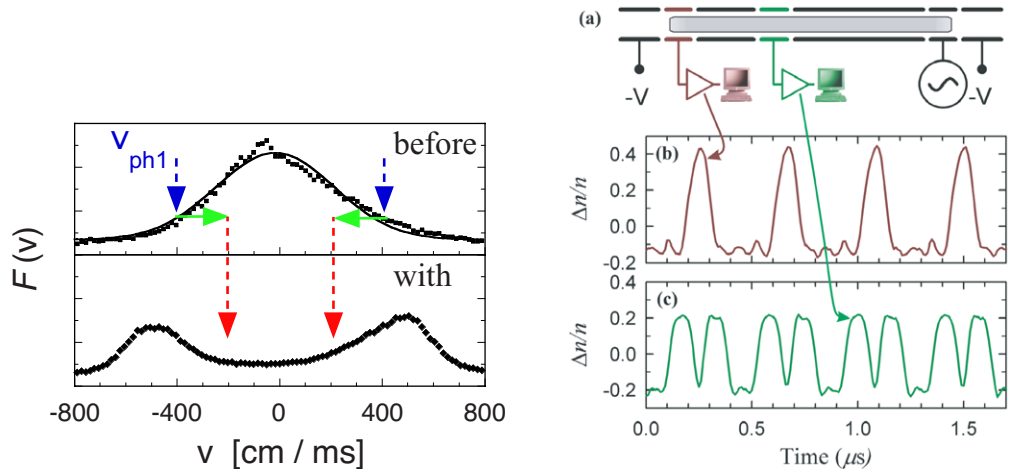

Figure 3 *Example of extreme modifications of the velocity particles distribution in ion plasma [9], and large amplitude cnoidal plasma waves measured in electron plasma [10]*