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	S

Indicate type of presentation desired at Town Hall Meeting.

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

Title:	Impact of Beat-Wave Processes for Plasma Science
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Co-Authors:	

**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)**

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

Because an understanding of the nonlinear beat-wave process is crucial to many areas of plasma research, it is a true frontier of plasma science. For example, the nonlinear mixing of two high power pump electromagnetic waves can result in the saturated driven stimulated Raman forward-scattering instability. This can be applied to produce the beat-wave driven electron plasma wave (EPW), whereby ultra-high longitudinal electric fields can be excited to efficiently accelerate injected charged particles.[1-3] Other applications of plasma-mixed beat waves include phase modulation by high-amplitude EPW to induce pulse compression,[4] or to provide beat-wave driven ion cyclotron wave heating of electric propulsion plasma.[5] A particularly important plasma science application of beat-wave mixing is its use for current drive, in which a beat-wave-driven EPW transfers momentum to plasma electrons. The high-frequency pump waves overcome the plasma shielding effect to impart an EPW with low phase velocity to efficiently transfer momentum to thermal electrons. At moderate power levels, low density plasma beat-wave experiment have demonstrated that quasi-linear Landau damping theory is applicable.[6] At higher power levels, computational studies have made quantitative predictions of magnetic fields strengths generated by specific configurations.[7] Advances in raw computing power and architecture, numerical

algorithms (PIC, hybrid, extended MHD), and software development in recent years combine to offer golden opportunities well poised to explore the very rich physics in these plasma regimes. Benchmarking such simulation results with comparable experiments is clearly a highly desirable goal for plasma science, and a frontier in plasma science.

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

The drivers for the beat-wave are high-frequency electromagnetic waves (pump waves) with frequencies well above the plasma frequency, $\omega_{pump} \gg \omega_{pe}$. The beat-wave process is the nonlinear formation of an internal wave at difference frequency $\Delta\omega = \omega_2 - \omega_1$, $|\Delta\omega| \sim \omega_{pe}$ and difference wave vector $\Delta\vec{k} = \vec{k}_1 - \vec{k}_2$, produced by pump waves at frequency and wavenumber $(\omega_1, \vec{k}_1)$ and $(\omega_2, \vec{k}_2)$. At the resonance condition, where the driving wave phase velocity matches the local electron thermal velocity, plasma density fluctuations and electrostatic fields become large, and grow exponentially in time. The theoretical understanding of the beat-wave generated plasma wave is provided by several pioneering papers.[1, 8]

The UC Davis research group has been investigating production of the EPW by plasma mixing for a considerable time. Initial experiments were performed using microwave sources in low-density plasma. This had the advantage of allowing direct observation of growth and decay of the beat-wave driven EPW, as shown in Figure 1. The beat-wave energy is found to be transferred to plasma electrons as measured using a particle-energy analyzer, as shown in Figure 2.

More recently, beat-wave experiments at UC Davis have shifted to much higher plasma densities, pump wave frequencies, and power levels. To be relevant for use in realistic magnetically confined plasmas with electron densities of 10^{14} cm^{-3} or more, beat wave frequencies of well above 90 GHz are required. In addition, high pump wave frequencies are desirable to avoid refraction or reflection during propagation into the plasma interior. From the source technology limit, a useful regime of high intensity sources is in the near-infrared range. Here TEA CO_2 lasers offer high efficiency as well as a wide selection of lasing lines, as shown in Figure 3. The CO_2 laser frequency of ~30 THz (~10.6 μm) is high enough for refraction-free operation in typical large-plasma experiments.

In our laboratory, two separate Model 601 TEA lasers operate as the source of pump waves. Each of these lasers is able to deliver a pulse with initial output power of ~100 MW for ~50 ns, and a tail of > 50 MW for ~500 ns (see Figure 4). Total pulse energy, delivered to the target, is typically > 25 J. One of these lasers operates in the oscillator mode at its natural wavelength of 10.6 μm while the other is operated as a grating-tuned oscillator. With grating-tuned operation, the difference frequency can be chosen to match the plasma frequency at different density regimes. For example, the 10P (8) and 10P (20) lines can be chosen to match a plasma density of 1.2×10^{15} cm^{-3}.

In addition, we have available a steady-state, low-power CO_2 laser for detection of beat-wave driven electron density fluctuations, this can be used as a scattering laser. Unlike collective scattering experiments of spontaneous plasma fluctuations, the beat-wave driven plasma wave has a well-defined frequency and wavenumber determined by the pump waves. This temporal and spatial coherence greatly eases the task of detecting the wave scattered by EPW-induced density fluctuations, as does the relatively large scattering angle resulting from the short beat wavelength, which is on the order of the Debye length.

Recent code simulation results have provided quantitative predictions of beat-wave current drive efficiency.[7, 9] To confirm results, experimental results should be compared with simulation. Using our TEA laser setup, these would include (1) verification of the power scaling of the beat-wave power with pump wave intensity; (2) measurement of the beat-wave amplitude as a function of difference frequency, using various lines of the TEA lasers; (3) measurement of the velocity distribution of beat-wave driven electrons; and (4) measurement of beat-wave driven plasma current The first two of these results would be determined by measurements of pump-wave depletion or laser scattering, as described above. Measurement of electron velocity distribution would use electrostatic energy analyzers, and current would be measured by fast pickup loops.

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

Combining with a standoff technique for assembling a plasma without boundaries,[10] the beat-wave current drive, when successfully developed, will enable magnetic fields of various geometries to be generated in these plasmas, also in a standoff manner, for a wide range of spatial and temporal scales. This will open up new frontiers in our exploration of magnetized plasmas in the laboratory in manners that have not been even dreamed of before, and that may have profound implications for fusion energy sciences as well as our understanding of the cosmos.

One application of beat-wave current drive that might have immense societal value is the seeding of current into dense target plasmas prior to their compression by external drivers. The ability to produce this seed current by a standoff method (drivers distant from walls) is a crucial aspect of the Magnetized Inertial Confinement (MIF) approach to controlled thermonuclear fusion. The societal advantages of controlled fusion are familiar to all who work in our field, and need no further explanation.

In addition to its use as a current driver, and as for experimental verification of numerical simulation, the use of nonlinearly-generated waves has the potential for new types of wave experiments in plasmas. Typically, a wave, which interacts strongly with plasma, propagates in a direction, which is strongly influenced by plasma properties. This may result in moderate refraction (electron cyclotron waves), mode conversion or damping (electron Bernstein waves, lower-hybrid waves), or even total reflection (plasma waves). Due to these effects, a wave of interest may be inaccessible to the plasma interior. The beat-wave method of wave generation largely eliminates the problem of accessibility, since the pump waves reach the plasma interior without significant refraction or absorption. Moreover, because the frequency and wave number of the pump waves is well defined, the frequency and wave number (and therefore phase velocity) of the spatial location of the beat wave is also well defined. The region of overlap of pump waves is also well defined, so that the beat wave source behaves much like an idealized Green's function of plasma wave theory. If the trajectory and amplitude of beat-wave driven waves can be measured, for instance by a scattering diagnostic, interior properties of even a large, hot plasma can be inferred locally, without the need for inversion techniques of line averaged measurements.

As a final advantage, by simple choice of difference frequency, the beat-wave technique can generate waves at frequencies where high-power conventional sources are scarce, such as the terahertz range. It may be possible to develop optimized configurations of pump wave and plasma targets, which can serve as a flexible, high-power, easily-tunable source of electromagnetic power in these difficult frequency ranges.

References (Maximum 1 page)

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6. Rogers, J.H. and D.Q. Hwang, *Measurements of Beat-Wave-Accelerated Electrons in a Toroidal Plasma.* Physical Review Letters, 1992. **68**(26): p. 3877-3880.
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10. Hsu, S.C., A.L. Moser, E.C. Merritt, C.S. Adams, J.P. Dunn, S. Brockington, A. Case, M. Gilmore, A.G. Lynn, S.J. Messer, and F.D. Witherspoon, *Laboratory plasma physics experiments using merging supersonic plasma jets.* Journal of Plasma Physics, 2015. **81**.

Figures (maximum 1 page)

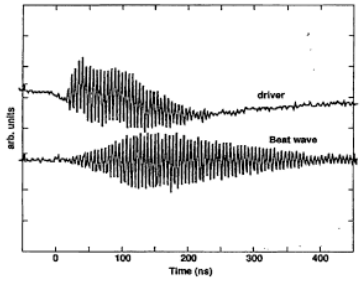

Figure 1: Beat-wave generation in low-density plasma with microwave sources.

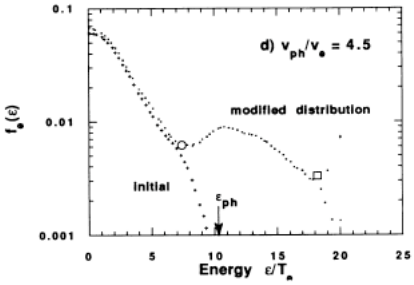

Figure 2: Electron energy distribution before and after beat-wave Landau damping.

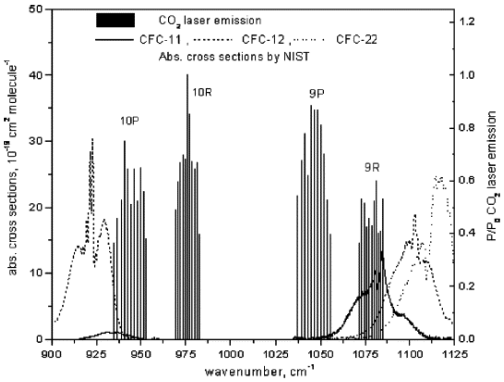

Figure 3: CO_2 laser emission lines spectrum.

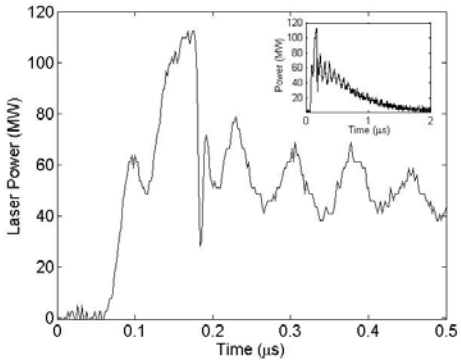

Figure 4: TEA CO2 laser power as a function of time. The peak power of ~100 MW lasts ~ 100 ns