Optical Mixing Generated EPWs and TEAWs: Exploring the Nonlinear Phase Space Physics of SRS and STEAS

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$\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$

$\frac{e^2}{\hbar c} \approx \frac{1}{137}$

Wente Vinyards
LPI Saturation
Workshop
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Electromagnetically Induced and Plasmon Induced Transparency: Exploring the Nonlinear Phase Space Physics of Plasmas via Optical Mixing Experiments

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$\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$ $\frac{e^2}{\hbar c} \approx \frac{1}{137}$

- **We imagine an optical mixing experiment where counter-propagating pump and probe beams cross in a gas jet (gas bag) or any other well characterized low density plasma. The frequency of the probe is chosen so as to drive an EPW *or* a TEAW for various $k\lambda_D$ values from 0.1 to 0.5.**

- **When the frequency at a given $k\lambda_D$ favors EPW, we expect SRS to be seeded, while if TEAW are favored, we expect to see STEAS seeded and amplified in a controlled fashion once the e^- VDF can be distorted enough to give rise to TEAW.**

- **By varying the amplitudes of the pump and probe we can establish the necessary conditions required in order to drive TEAW to Transparency. The evidence would come from the amplified small signal transmission of the probe, and dependence on the ω & k of the TEAW drive.**

- **We would thus be probing the actual velocity distribution's evolving shape or *phase space dynamics* by the interaction *between* these modes and comparison to Vlasov simulations.**

- **By simultaneously launching two probe beams at *both* the EPW *and* TEAW frequencies staggered in time (using Raman cells), and then by varying their relative amplitudes and their ω & k one can study the cooperative phenomena that lead to the creation of STEAS and SRBS.**

SRS & STEAS Mimicking, Ponderomotive Force Driven, Vlasov-Poisson System of Equations

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$\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$ $\frac{e^2}{\hbar c} \approx \frac{1}{137}$

Vlasov

$$\frac{\partial f_e^{1D}}{\partial \bar{t}} + \bar{v}\,\frac{\partial f_e^{1D}}{\partial \bar{z}} - \left(E - \frac{\partial \psi_{PF}}{\partial \bar{z}} \right) \frac{\partial f_e^{1D}}{\partial \bar{v}} = 0$$

$$\bar{t} = \omega_{pe} t;\ \bar{z} = z/\lambda_{De};\ \bar{v} = v/v_{th}$$

$$\frac{\partial E}{\partial \bar{z}} = 1 - \int f_e^{1D}\, d\bar{v}$$

Poisson

$$\int v^2 f_e^{3D}\, dv^3 = 3\, v_{th}^2$$

$$\psi_{PF} = \sum_{\#driver\ modes} \psi_{AMP}^{(i)} \cos\left(\bar{k}_i \bar{z} - \bar{\omega}_i \bar{t}\right)$$

$$\psi_{AMP} = \frac{\left(\frac{eE_0}{m\omega_0}\right)\left(\frac{eE_s}{m\omega_s}\right)}{v_{th}^2}$$

$$\psi_{AMP} = \frac{0.037}{T_{e,keV}} \left(I_{0,10^{14}\ W/cm^2}\, \lambda_{0\ \mu m}^2 \right) \sqrt{\frac{I_s}{I_0}} \left(\frac{\lambda_s}{\lambda_0} \right)$$

$$\frac{\partial \psi_{PF}}{\partial \bar{z}} = -\sum_{\#\ driver\ modes} \psi_{AMP}^{(i)}\, \bar{k}_i \sin\left(\bar{k}_i \bar{z} - \bar{\omega}_i \bar{t}\right)$$

What Questions Can We Answer With Vlasov Simulations?

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- How can one drive TEAW's? Who does the VDF Distortion? Deus Ex Machina so far in the literature...
- How much energy does it take to drive a TEAW to appreciable levels?
- How nonlinear does an EPW have to get in order to do this driving?
- Does the EPW have to reach in and distort phase space all the way down where TEAWs live, directly, or are there less violent more subtle means?
- Does sub-harmonic generation do the trick? What resonance conditions come into play? How clean do these resonances have to be?
- How big can a stable TEAW get? How large a STEAS/SRS scatter ratio can one achieve? How low does the $k\lambda_D$ of the SRS have to be (in some DLM VDF) before it can trigger TEAW generation?
- What happens in inhomogeneous plasmas? Wavepackets, non-periodic regimes? Finite bandwidths? > 1D?

V-P Simulation of PF Driven EPW & TEAW at $k\lambda_D$~0.4 for Drive Amplitudes of 0.03 & 0.01 Respectively

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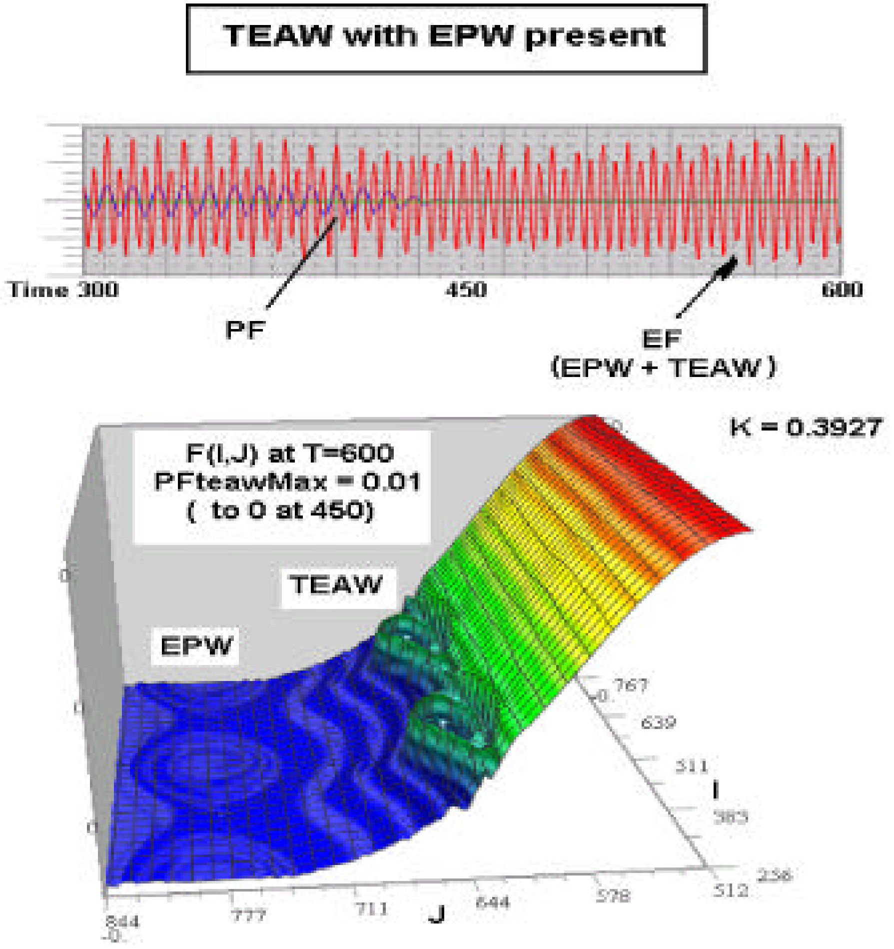
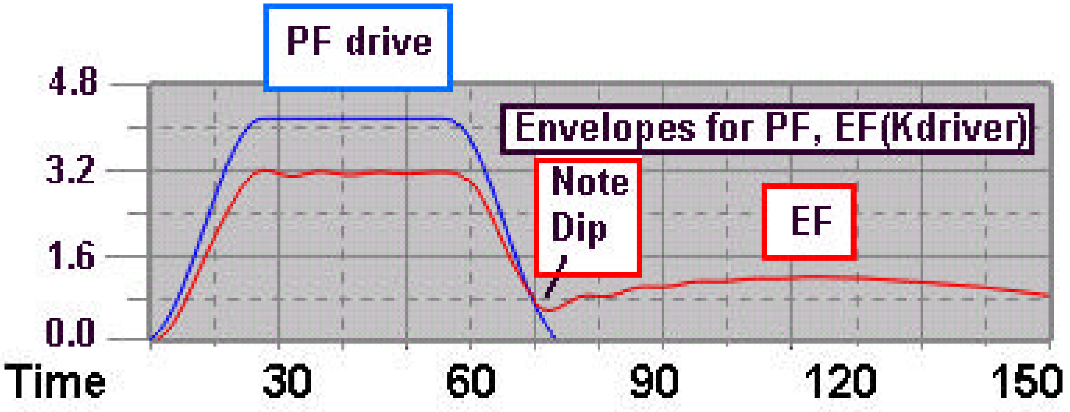
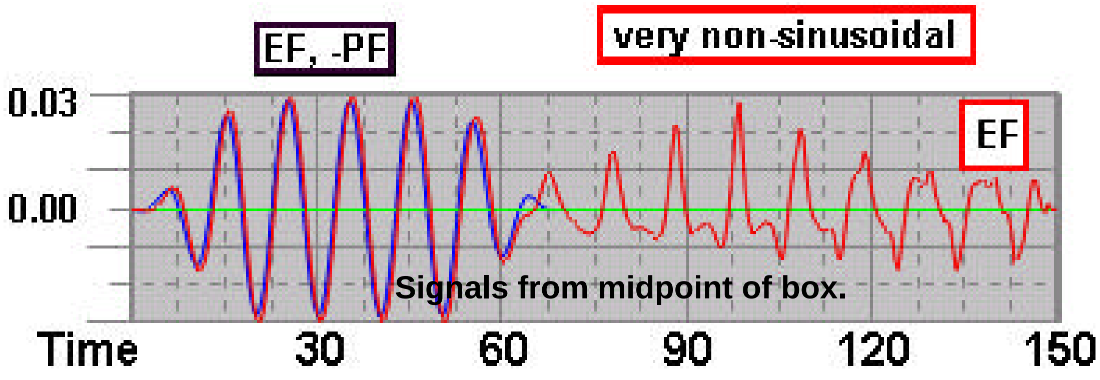


- Coexistence of TEAW and EPW after the drive of the EPW has been turned off at t=300 and after the TEAW drive has been turned off at t=450.
- There appears to be a minimum TEAW drive amplitude required in order to give rise to a stable mode that survives the drive.
- This is unlike Holloway & Dorning, Schamel or Rose’s small amplitude “perturbative” results where VDF distortions are legislated.

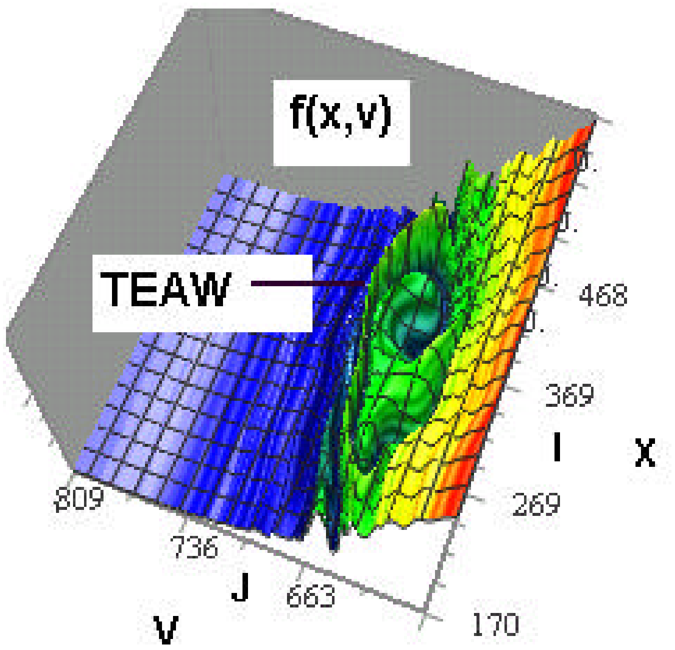
TEAW Driven Somewhat Over their “Soft” Threshold Hobble & Barely Survive

(Max PF here is 0.030)





F(x,v) at T=150

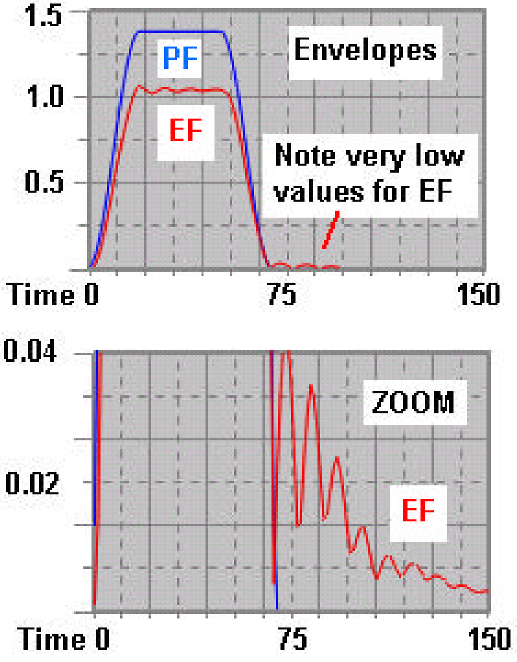


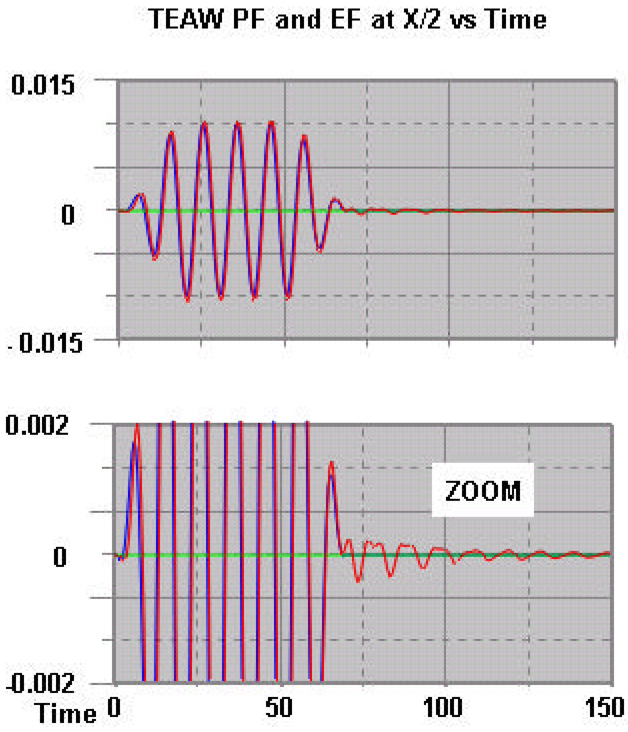
Driven TEAW Below the "Soft" Threshold Die Once their Drive Is Turned Off

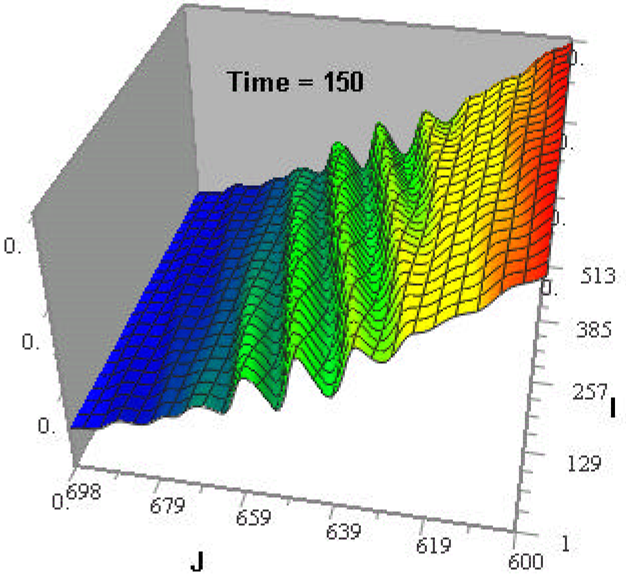
(PF max here is 0.010, "soft" threshold ~ 0.017)

F(x,v), T= 150

Classic phase space convection. No Trapping.



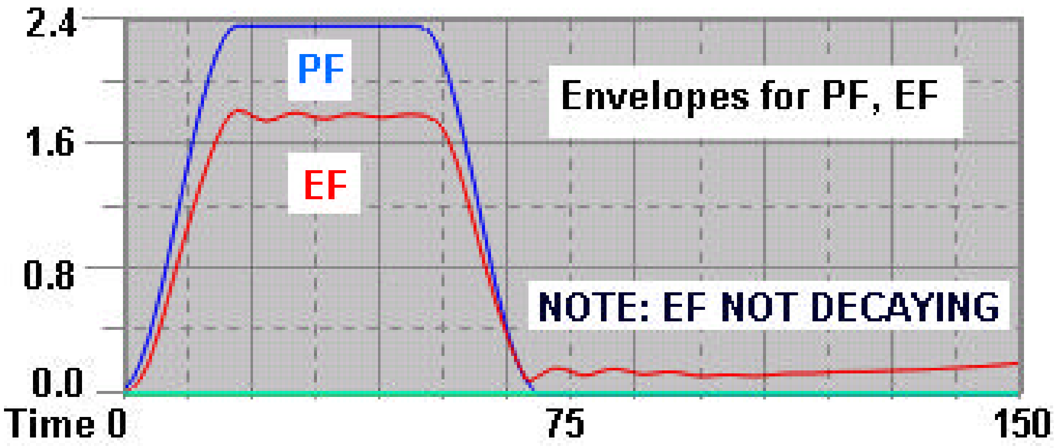


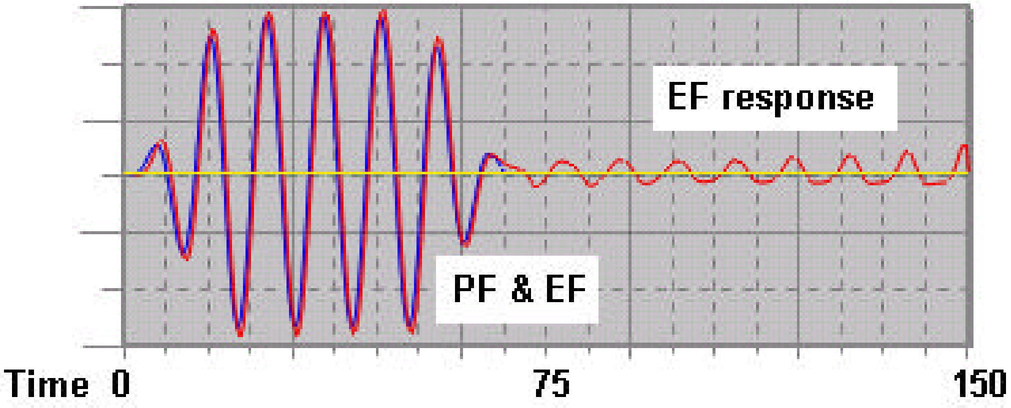


TEAW Driven at the “Soft” Threshold: Plasma Is Hesitant: to Decay or Form Phase Space Vortices?

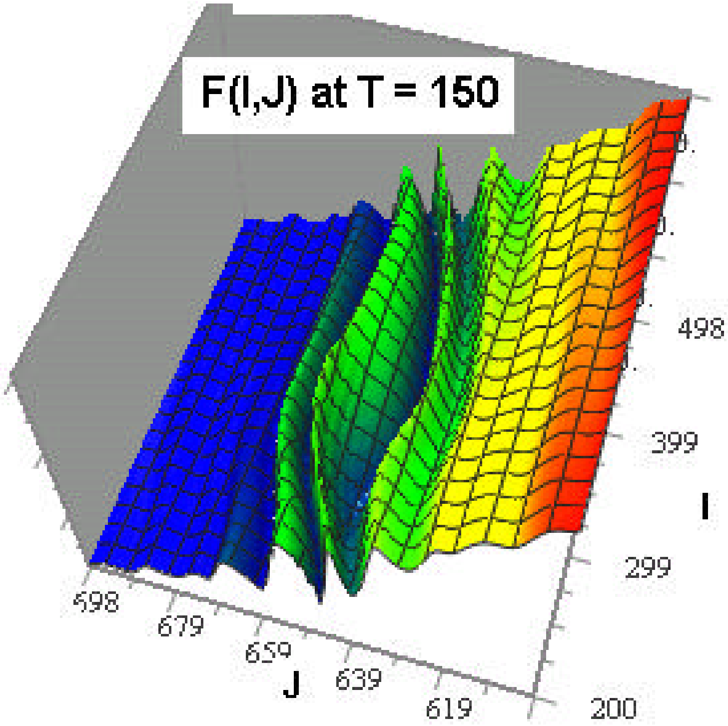
Max PF = 0.017

TEAW, K=0.39...





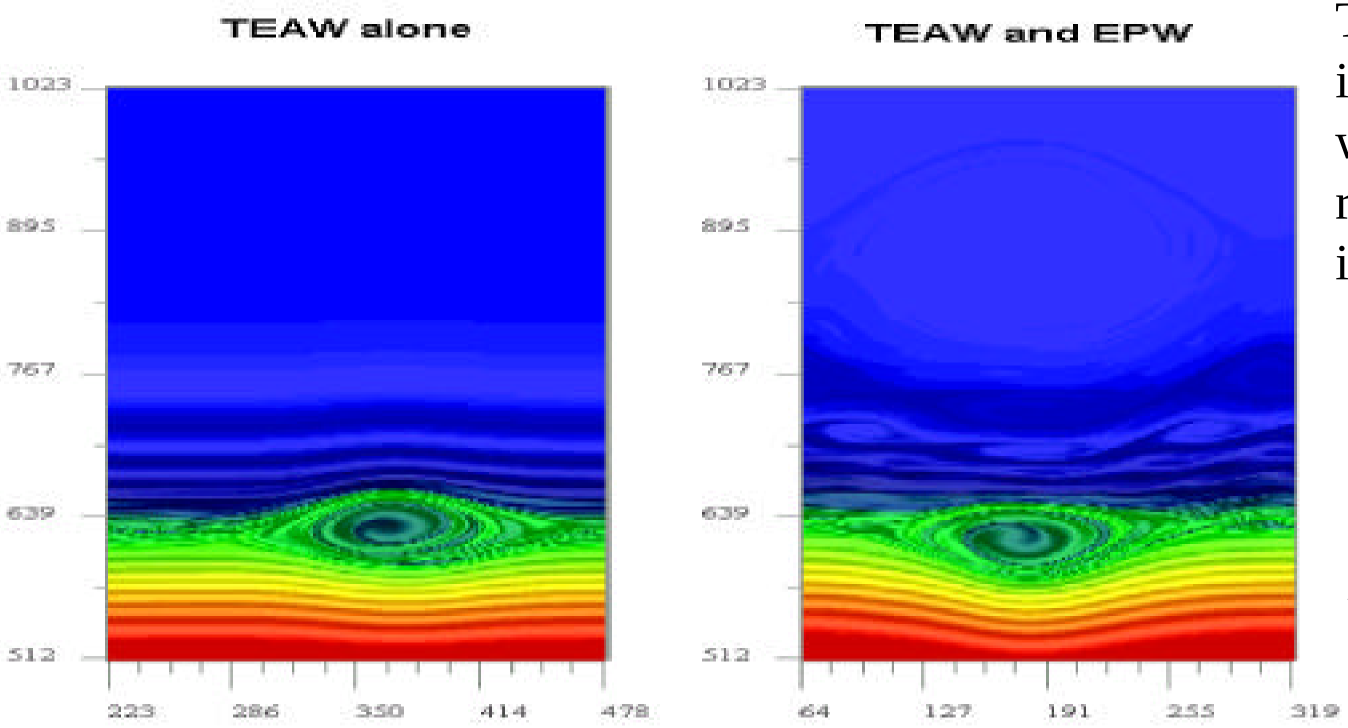
PF(max) = 0.017 gives a marginal TEAW, surviving well after PF => 0



Capturing the Interaction Between Driven and Released EPW & TEAW

$k\lambda_D = 0.26$, $\omega_{TEAW}:\omega_{EPW} = 1:3$

The gradual invasion of the TEAW space by the evolution of a driven and released EPW is shown in this snapshot comparing the phase spaces of TEAW formation without and then with a pe-existent EPW.



TEAW drive amplitude is higher at 0.03 while the highly resonant EPW's is 0.003.

There is ample parameter space left to explore to establish the resonant entanglements between these modes.

EPW and TEAW Coexistence & Interaction Are Strongly Affected by the Initial e$^-$ VDF

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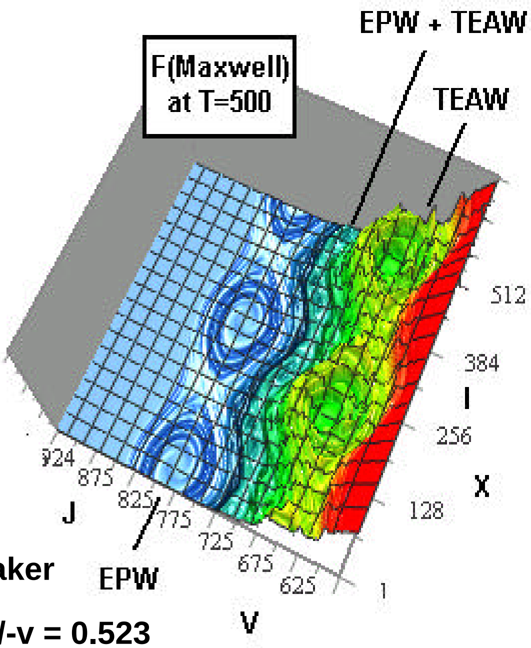
At high K (=0.3927 = π / 8) the distribution function shape makes a big difference to the EPW. It is presumably this that affects the interacting TEAW.

TEAW is stronger +/- v = 0.523 (vphase = 1.54)



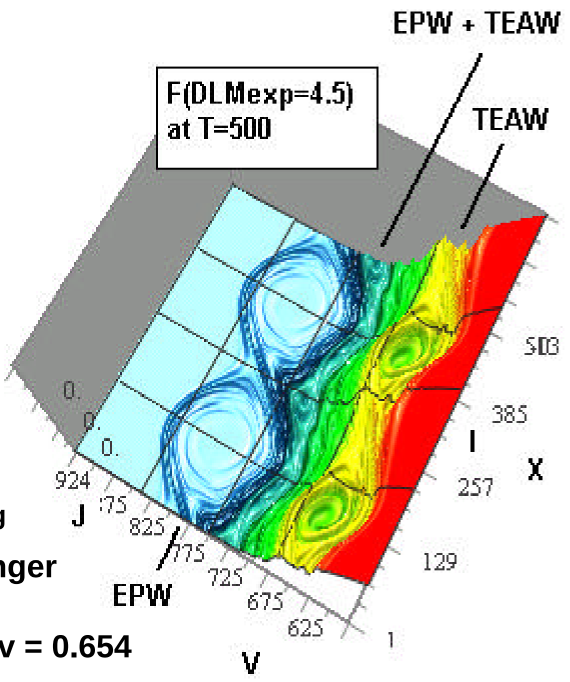
More

damping

weaker

+/-v = 0.523

TEAW is weaker +/- v = 0.351



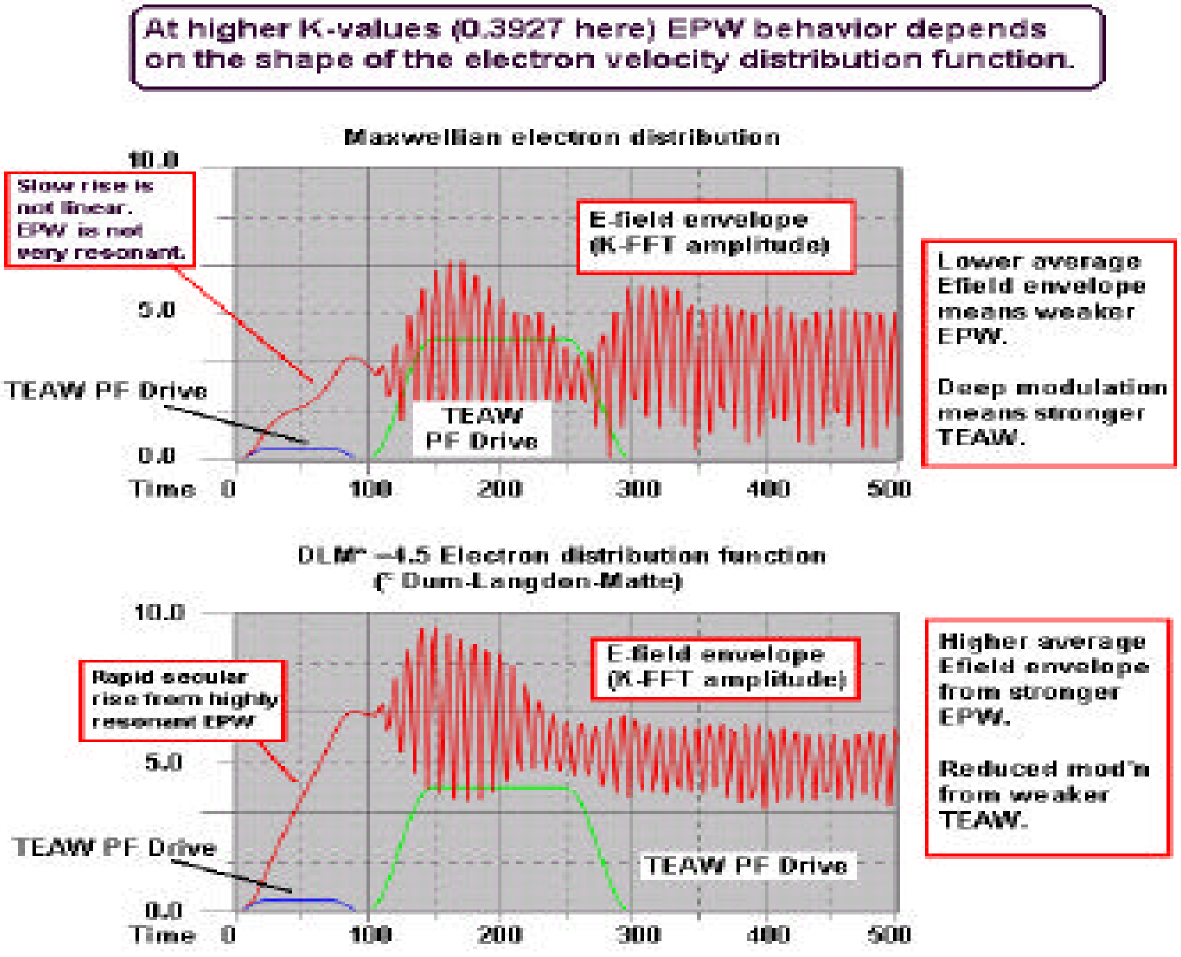
Less

damping

stronger

+/-v = 0.654

Effect of Initial Electron Velocity Distribution Function on Generation and Interaction of EPW + TEAW



At higher K-values (0.3927 here) EPW behavior depends on the shape of the electron velocity distribution function.

Maxwellian electron distribution

Slow rise is not linear. EPW is not very resonant.

E-field envelope (K-FFT amplitude)

Lower average Efield envelope means weaker EPW.

Deep modulation means stronger TEAW.

DLM* ~4.5 Electron distribution function (* Dum-Langdon-Matte)

Rapid secular rise from highly resonant EPW

E-field envelope (K-FFT amplitude)

Higher average Efield envelope from stronger EPW.

Reduced mod'n from weaker TEAW.

Initial e$^-$ VDF Is the Integral over Perpendicular Velocities of a 3D Isotropic DLM e$^-$ VDF

$$f_e^{1D}\left(\frac{v_{//}}{\alpha_E v_{th}}, n, t=0\right) = \frac{N_{e0}}{v_E}\, C_{1D}(n)\,\Gamma\left[\frac{2}{n}, \left(\frac{v_{//}}{\alpha_E v_{th}}\right)^n\right]$$

$$C_{1D}(n) = \frac{1}{2}\left[\frac{\Gamma\left(\frac{5}{n}\right)}{3\Gamma^3\left(\frac{3}{n}\right)}\right]^{\frac{1}{2}}$$

$$\alpha_E = \left[\frac{3\Gamma\left(\frac{3}{n}\right)}{\Gamma\left(\frac{5}{n}\right)}\right]^{\frac{1}{2}}$$

$$f_e^{3D}(\mathrm{v}) = C_{3D}(n)\,\frac{N_{e0}}{\mathrm{v}_{th}^3}\exp\left[-\left(\frac{|\mathrm{v}|}{\alpha_e \mathrm{v}_{th}}\right)^n\right]$$

$$C_{3D}(n) = \left(\frac{1}{4\pi\,\alpha_E^3}\right)\left[\frac{n}{\Gamma\left(3/n\right)}\right]$$

$$\Gamma\left[\frac{2}{n}, \left(\frac{v_{//}}{\alpha_E v_{th}}\right)^n\right] \equiv \int_{\left(\frac{v_{//}}{\alpha_E v_{th}}\right)^n}^{\infty} e^{-u}\, u^{\frac{2}{n}-1}\, du$$

An Incomplete Gamma Function

$C_{1D}(2, 2.5, \ldots, 5) = \{0.398942, 0.328115, 0.274279, 0.233695,$
$0.202602, 0.178276, 0.158849\}$

$\alpha_E(2, 2.5, \ldots, 5) = \{1.41421, 1.65967, 1.82296, 1.93489,$
$2.01392, 2.0712, 2.11366\}$

What Do 1D Projections of 3D DLM e^- VDF Look like? How About EPW Damping Rates and IAW Frequency Shifts?

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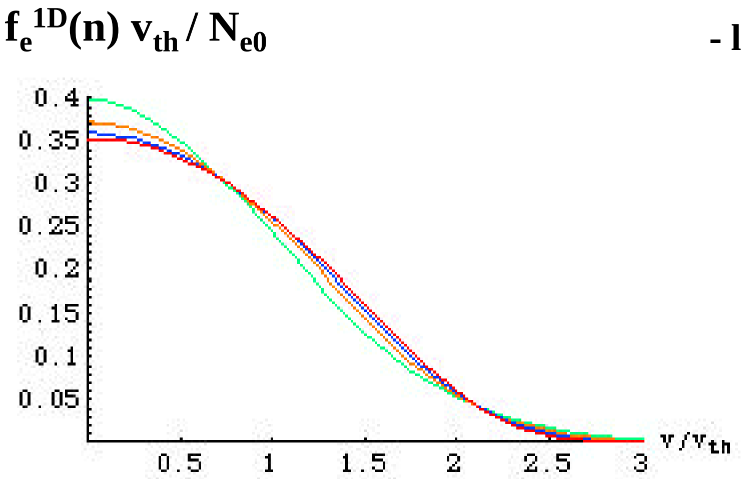

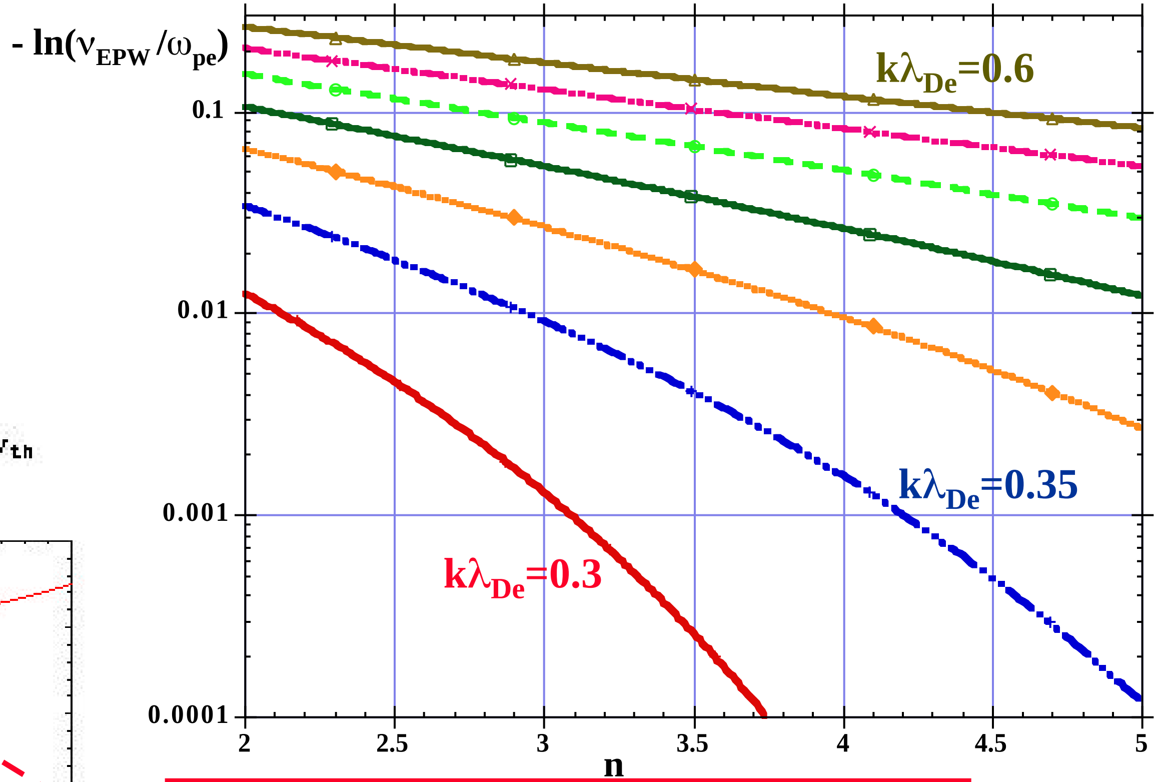

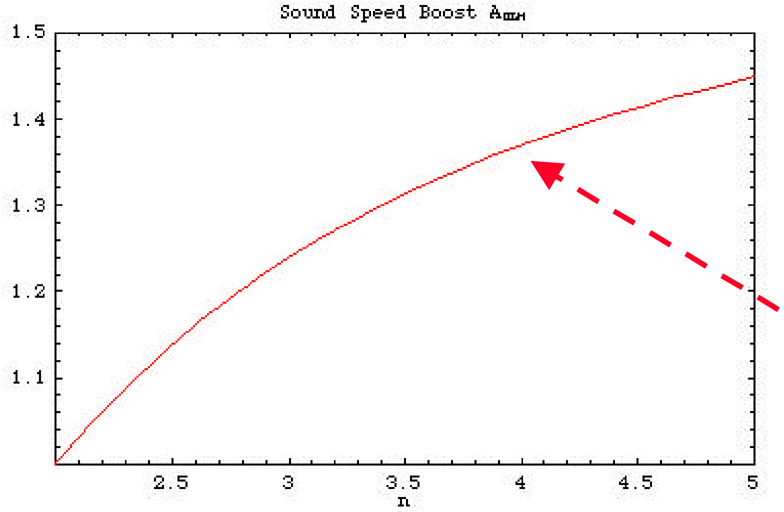

$$A_{\mathrm{DLM}}(n) = \frac{c_s^2\big|_{\mathrm{DLM}}}{c_s^2\big|_{\mathrm{Maxwellian}}} = \frac{3\,\Gamma^2(3/n)}{\Gamma(1/n)\,\Gamma(5/n)}$$

LANL Trident STEAS Experimental Conditions and their Translation into 1D Driven V-P Simulation Parameters

C_8H_8, SHS f/4.5

D. S. Montgomery et al., *Phys. Rev. Lett.*, <u>87</u>, 155001 (2001)

$$\psi_{AMP} = \frac{0.037}{T_{e,keV}}\left(I_{0,10^{14}\,W/cm^2}\lambda^2_{0\,\mu m}\right)\sqrt{\frac{I_s}{I_0}}\left(\frac{\lambda_s}{\lambda_0}\right)$$

$$\psi_{AMP} \approx (0.53, 2.6)\sqrt{\frac{I_s}{I_0}}\left(\frac{\lambda_s}{\lambda_0}\right)$$

$$\lambda_{0,\mu m} = 0.527 \qquad 0.02 < \frac{n}{n_c} < 0.03$$

$$T_{e,keV} = 0.35 \pm 0.05$$

$$5 < I_{0,10^{14}\,W/cm^2}\lambda^2_{0,\mu m} < 25$$

$$\omega_{TEAW} \approx 1.31\; k_{TEAW}\, v_{th}$$

$$\omega_{EPW} \approx \omega_{pe} \qquad k\lambda_{De} \approx 0.27$$

$$\frac{\omega_{EPW}}{\omega_{TEAW}} \approx 2.83$$

$$\sqrt{R_{\min}} < \psi_{AMP} < 5\sqrt{R_{\max}}$$

$$0.5\% < R_{SRS} < 7\%$$

$$R_{STEAS} \sim 0.002\%$$

$$5\times 10^{-3} < \psi_{AMP} < 1.3$$

The Configuration of our Omega Blue-Green OMC SSI Experiments

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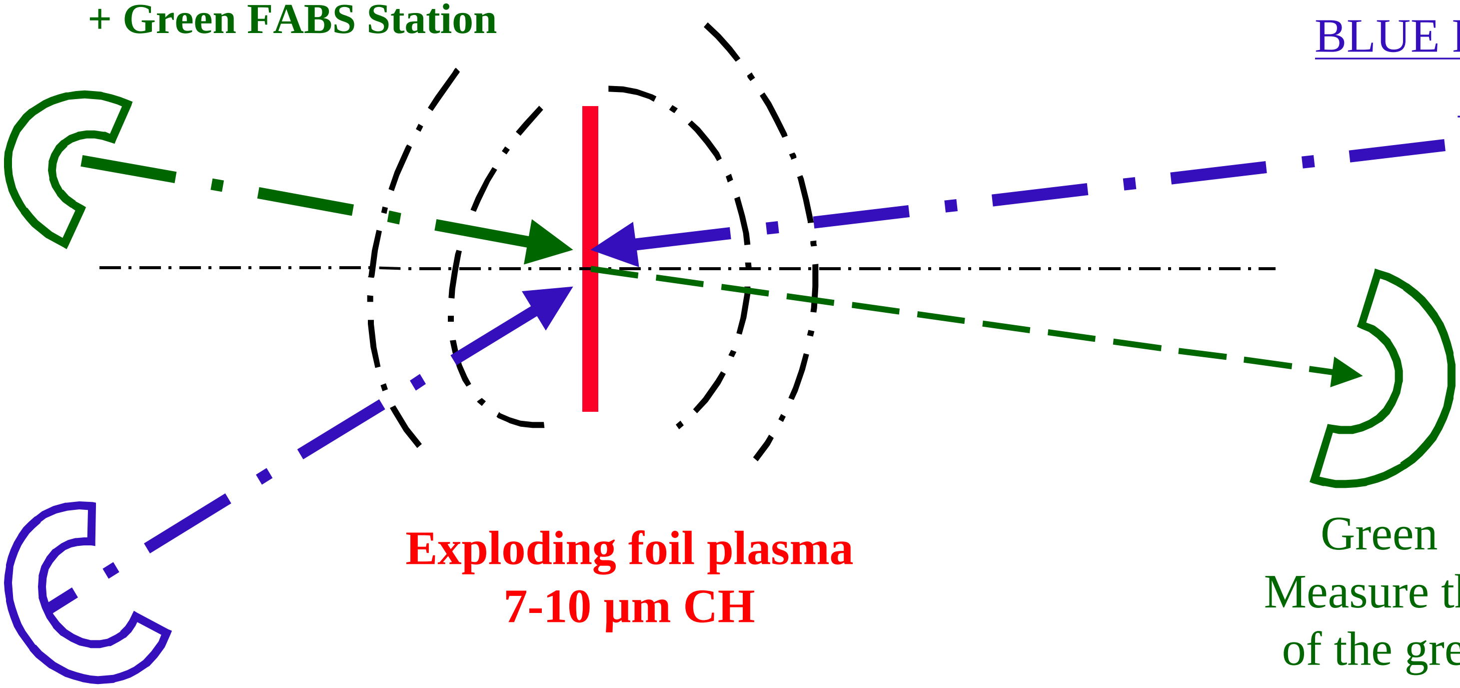


GREEN PROBE BEAM
(BL25) @ P 9
+ Green FABS Station

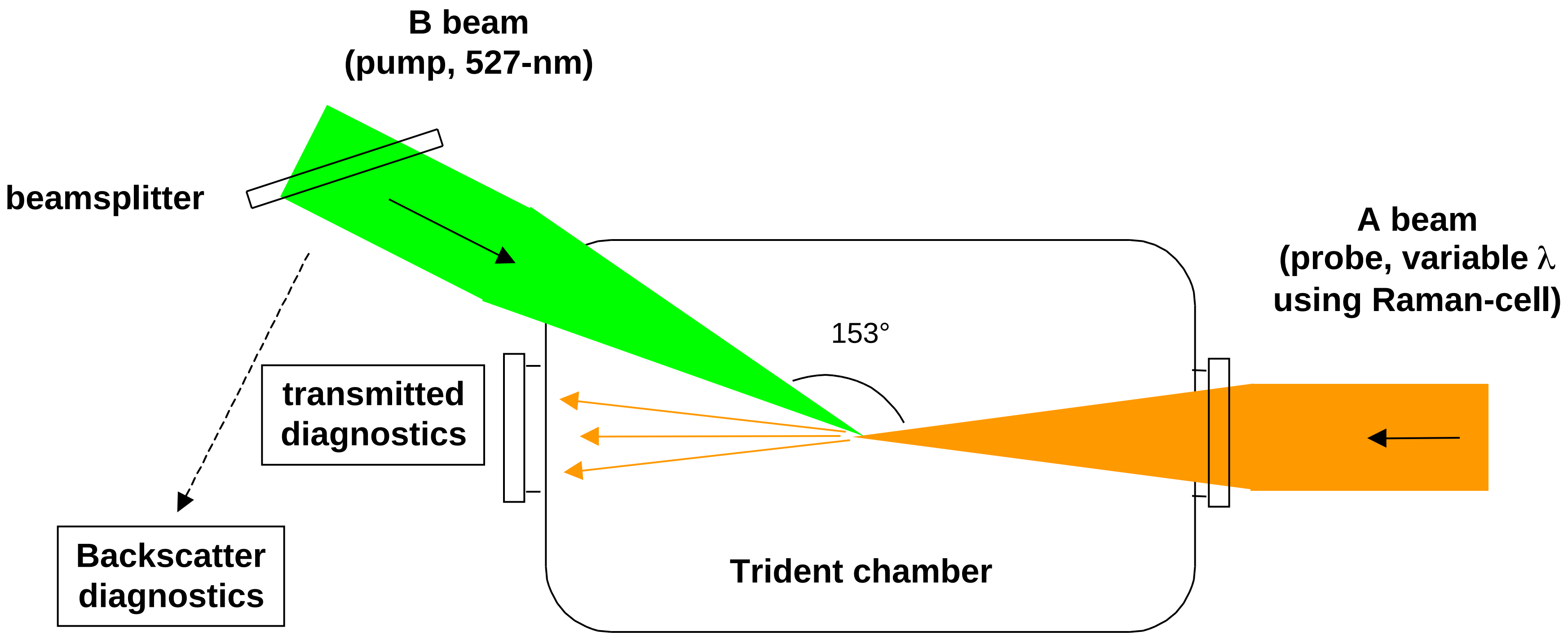
BLUE PUMP BEAM
BL 55

Exploding foil plasma
7-10 µm CH

Green TBD station
Measure the transmission
of the green probe beam

BLUE SRS GENERATING BEAM
BL12
+ Blue FABS station

Experimental Configuration For EPW & TEAW Optical Mixing Generation on the Trident Laser System



B beam
(pump, 527-nm)

beamsplitter

A beam
(probe, variable λ
using Raman-cell)

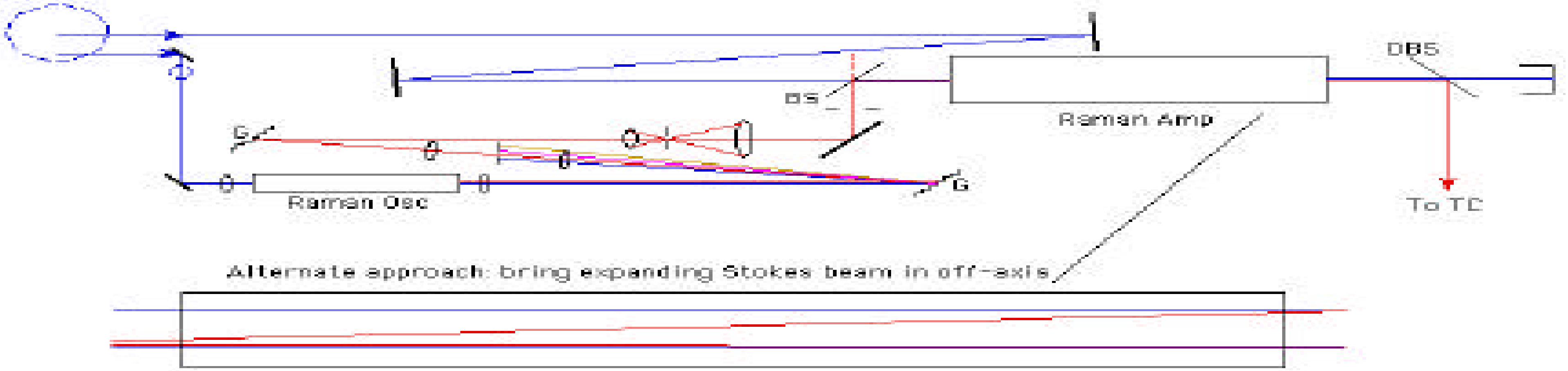
153°

transmitted diagnostics

Backscatter diagnostics

Trident chamber

The Raman Cell Configuration Itself And the Table of Wavelength Possibilities on Trident (N. Kurnit)



Single Stokes shift

Transition	Shift (cm^{-1})	Wavelength (nm)	Gain(cm/MW)
H_2 $S_0(1)$	586.85	543.82	8.3×10^{-4}
SF_6 Q branch	775	549.44	1.5×10^{-5}
CF_4 Q branch	908	553.49	4.5×10^{-6}
O_2 Q(7)	1555.51	574.06	6.8×10^{-6}
O_2 Q(9)	1554.97	574.04	6.8×10^{-6}
N_2 Q(6)	2330.03	600.77	3.2×10^{-6}
N_2 Q(8)	2329.37	600.75	3.2×10^{-6}
CH_4 Q branch	2917	622.73	9.0×10^{-5}
D_2 Q(2)	2987.17	625.46	6.8×10^{-4}
NH_3 Q branch	3334	639.33	1.1×10^{-6}
H_2 Q(1)	4155.22	674.76	1.4×10^{-3}

Double Stokes shifts

N_2 2xQ(6)	4660.06	698.55
CH_4 2xQ branch	5834	760.96
D_2 2xQ(2)	5974.34	769.17
NH_3 2xQ branch	6668	812.52
H_2 Q(1)+D_2 Q(2)	7142.39	845.10
H_2 2xQ(1)	8310.44	937.66

Doing Our Raman Cell and Kinetic Dispersion Relation Homework: Lines That Matter for EPW and TEAW OMG

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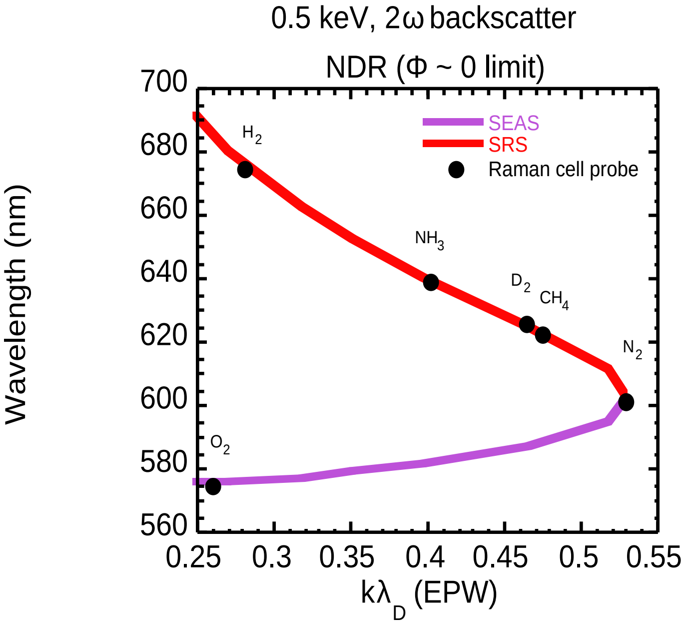
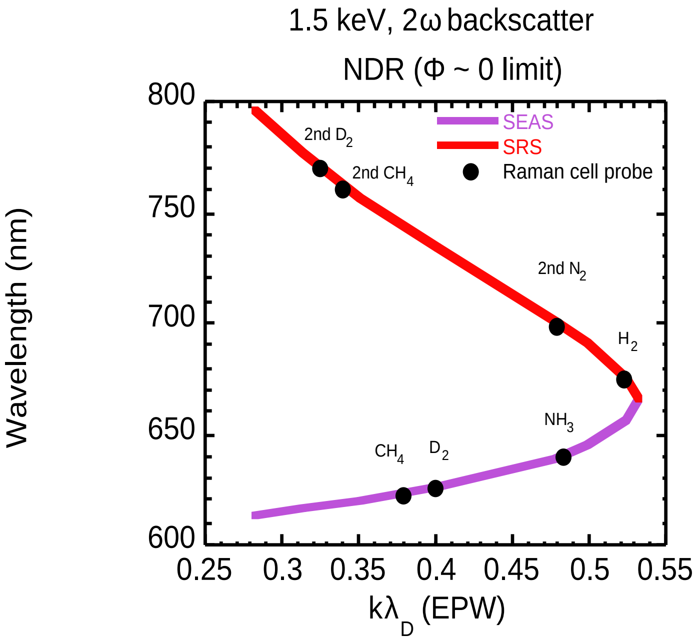
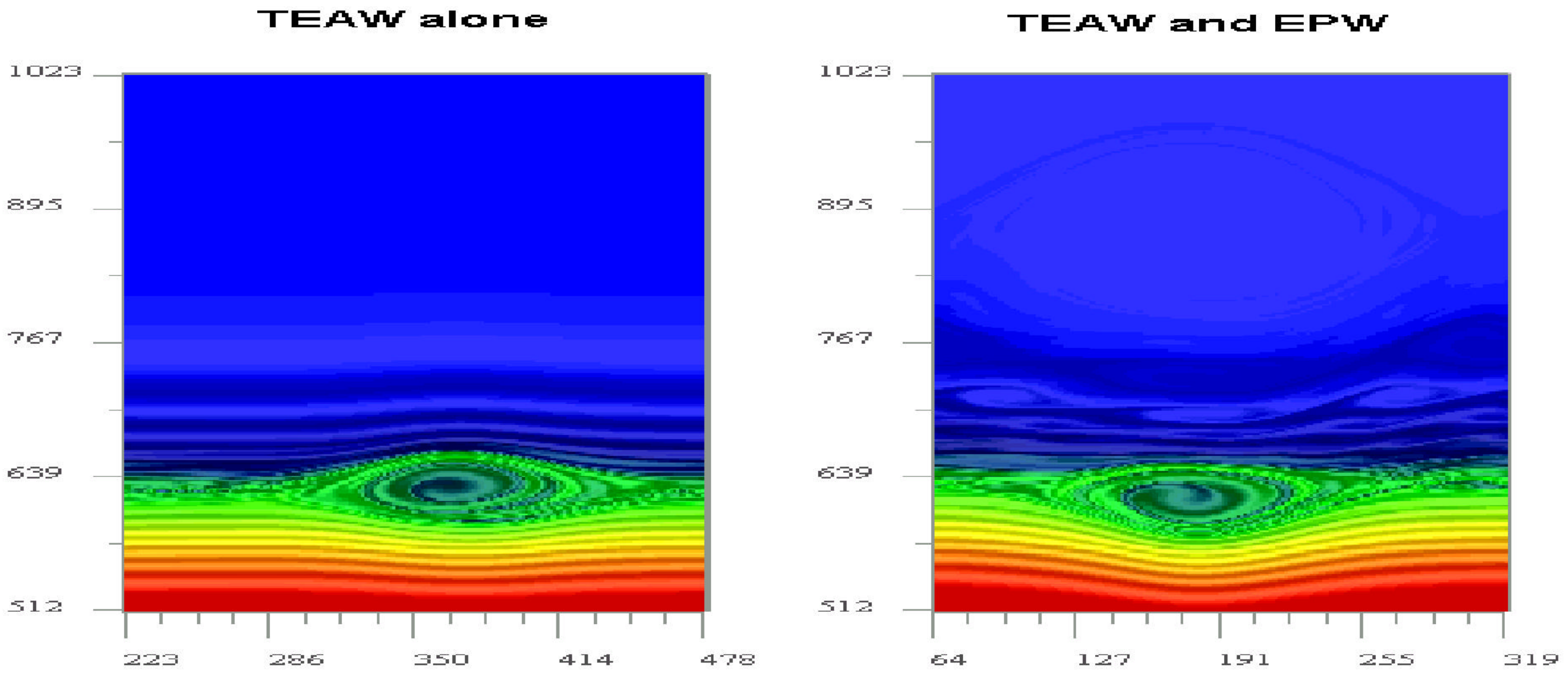




The Phase Space Physics of TEAW/EPW Interaction We Wish to Explore



The Parameter Space Worth Exploring Even in these Homogeneous Plasma & Uniform Drive Amplitude Cases Is Large

- Amplitude and duration of the EPW PF drive (2)
- Amplitude and duration of the TEAW PF drive (2)
- Frequency and wavenumber of the EPW PF drive (2)
- Frequency and wavenumber of the TEAW PF drive (2)
- Ramp up and ramp down characteristics of the EPW PF drive (2)
- Ramp up and ramp down characteristics of the TEAW PF drive (2)
- The initial e^- VDF characterized by the DLM exponent n_{DLM} (1)
- There are therefor 13 independent parameters to vary and many have wide dynamic ranges (eg. $0.1 < k\lambda_D < 0.6$, $0.0001 < \Phi_{amp} < 1$, $2 < n_{DLM} < 5$)
- This estimate ignores varying the shape of the temporal envelopes being used (Sum of two Tanh functions per envelop at present)