Kinetic Theory in Laser Plasma Interactions: Fokker Planck, Vlasov & Fluid Moment Simulations and Their Future Prospects

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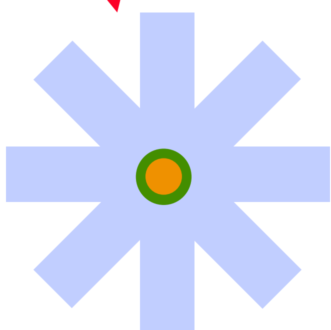
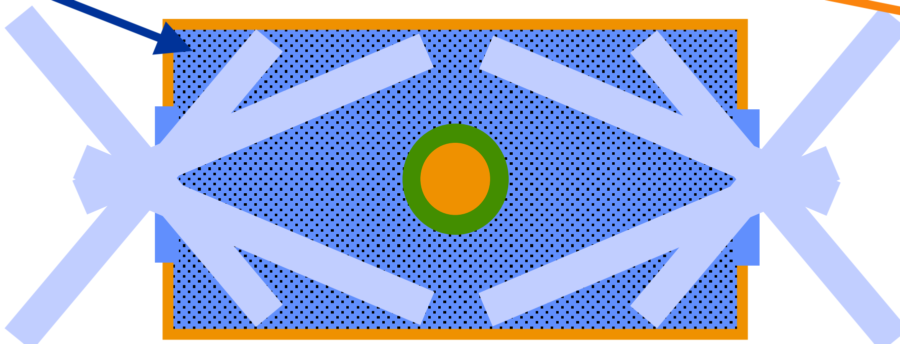
$\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$ $\frac{e^2}{\hbar c} \approx \frac{1}{137}$

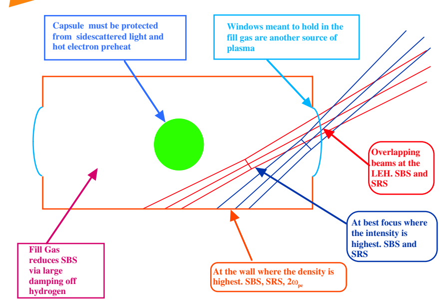
Three Dominant Geometries of Interest to the ICF Community: DD,ID & HTH



Direct Drive

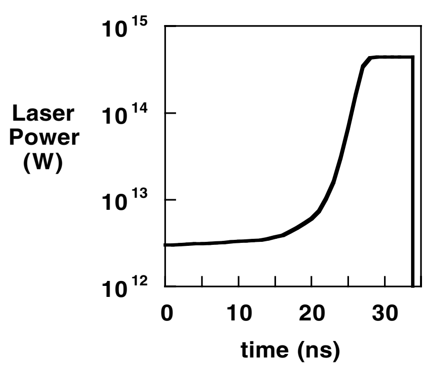


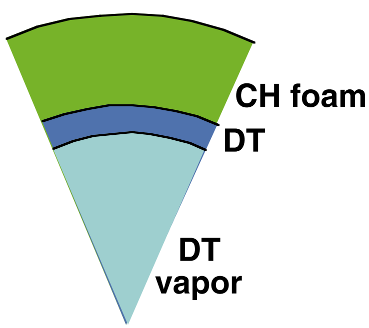
Indirect (Radiation X-Ray) **Drive**



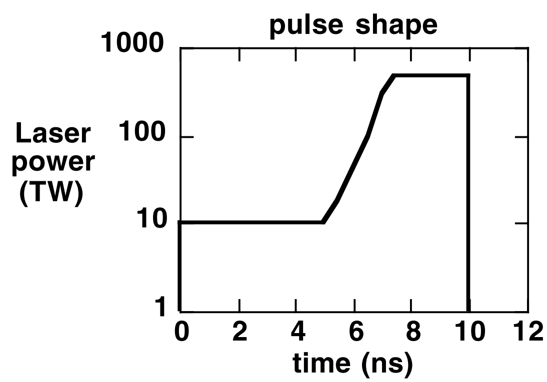
High Temperature Hohlraums have denser plasmas and higher intensity lasers

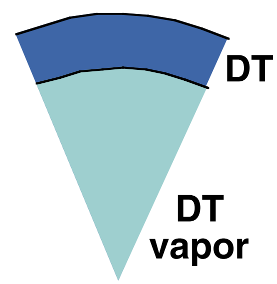
Schmitt Design: Low-density CH foam ablator; shock preheating 0.25 µm





Verdon Design: DT ablator; shock preheating 0.35µm





What is LPI in LSP and How Does it Impact ICF Ignition Physics?

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- Laser-Plasma Interactions in long scale length (~ mm) plasmas and multi-nsecs laser pulses consist of parametric instabilities such as SRS, SBS and $2\omega_{pe}$ as well as filamentation which involve EMWs, EPWs and IAWs.
- These processes can turn the plasma into a very expensive O(> $ 10^9) mirror &/or sabotage beam phasing in ID ICF and HTH. They can also preheat the fuel in DD and ID ICF (or the physics package in HTH by producing energetic (multi keV or even MeV, hot) electrons and hard X-rays .
- SRS and SBS are very likely to occur in sub-quarter-critical density, long density and velocity scale length plasmas, together with filamentation breaking up the beam into a smaller but hotter series of non-stationary spots. All these processes are likely under conditions envisaged in the NIF and LMJ ID and HTH targets.
- For DD, $2\omega_{pe}$ is more of a concern since quarter critical plasmas will exist but single beam laser intensities will not be as high as in ID and HTH.

What Aspects of Kinetic Theory Are of Most Interest in LPI in LSP?

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- Non-local heat transport and its effects on parametric instabilities in structured laser beams. (FP Simulations)
- Nonlinear saturation of PIs due to VDF changes, trapping, phase space vortex structure which linear theory can not see. (Vlasov Simulations)
- Acceleration of particles, wave properties changing under the combined influence of kinetic and fluid degrees of freedom: Cascade/ Collapse/ Secondary Instabilities/ Significant Damping Changes and Frequency Shifts/ Phase Space structural Changes/ Sideband instabilities... (Hybrid Simulations)
- Many champions of this sort of work: FP: Matte, Epperlein, Town, Kingham; Vlasov: Bertrand, Ghizzo, Johnston; PIC: Mori, Still, Vu, Dawson, Forslund, Kruer, Estabrook, Lasinski, Langdon...
- δf codes: can they work with EPWs and IAWs correctly in a hybrid manner? Valeo,Brunner, Krommes. Could future advances include NLHT Correctly?

Some Grand Challenges in Simulating Parametric Instabilities in Long Scale length Plasmas

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- Level of physical description necessary to predict what multiple interacting waves will do in large scale plasmas is an open area of research. Computer hardware advances will *NOT* be enough to tackle these challenges.
- Kinetic degrees of freedom, phase space physics, wave-particle interactions and collisional non-local heating effects complicate the task of relying on the most trivial modes of description, namely, bare 2-3 fluid moment equations.
- Non-fluid degrees of freedom dictate heat transport and energy transport in hot electrons, nonlinear interaction and saturation mechanisms of parametric instabilities and other essential elements of laser-plasma interaction physics necessary to understand the interaction of multiple crossing laser beams in hot and long scale length plasmas.
- Perhaps a good understanding of this physics will lead the way to hybrid models where kinetic theory is incorporated in a moment like set of eqns. But there is no a priori guarantee that this will be so.

Two Types of Problems Highlight the Crucial Role Kinetic Theories Play in LPI in LSP Physics

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- **Problem I: Combined Physics of filamentation and 2D non-local heat transport in laser hot spots affecting Stimulated Brillouin BackSscatter (SBBS).**
- **Nonlinear fluid simulations: Filamentation with nonlinear ion motion and SBFS. Generate intensity profiles (using Schmitt's PONHF2D code) every ps to be used to calculate the heating profile via FP simulations.**
- **Fokker Planck Simulations: 2D Cartesian Geometry, using Kingham's IMPaCT code without having to set J=0 and inside filamented intesity profiles.**
- **Backscattering Wave Equation Simulations: Use both intensity and temperature profiles in SOFTSTEP to compute SBBS gain in the strong IAW damping limit including 2D inhomogeneity & diffraction. Potentially beneficial to HTH targets!**
- **Problem II: Vlasov-Poisson and V-Maxwell simulations of SRBS and STEAS**
- **High frequency response of a plasma in the deeply nonlinear regime where phase space holes and clumps give rise to "new" kinetic modes? Use Ghizzo's V-P SE Code.**
- **Understand the NL evolution of EPWs in order to model SRS and $2\omega_{pe}$.**

Dave Montgomery's Trident Single Hot Spot Experiments

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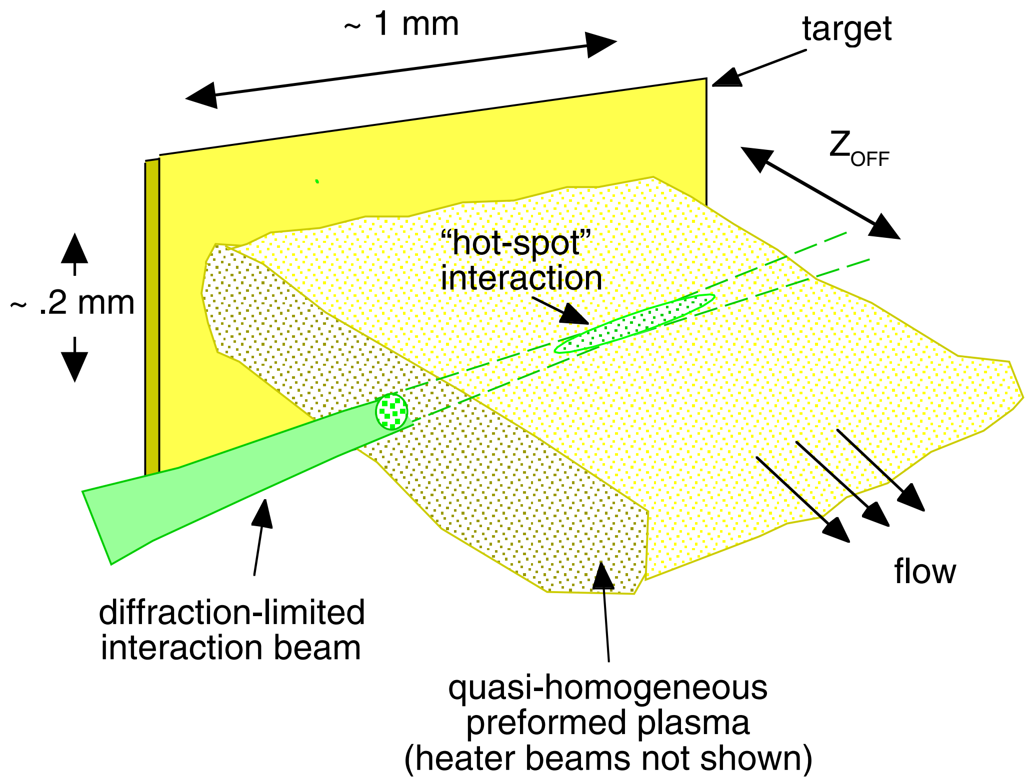
Montgomery et al., Laser Part. Beams **17**, 349 (1999), PRL **84**, 678 (2000)

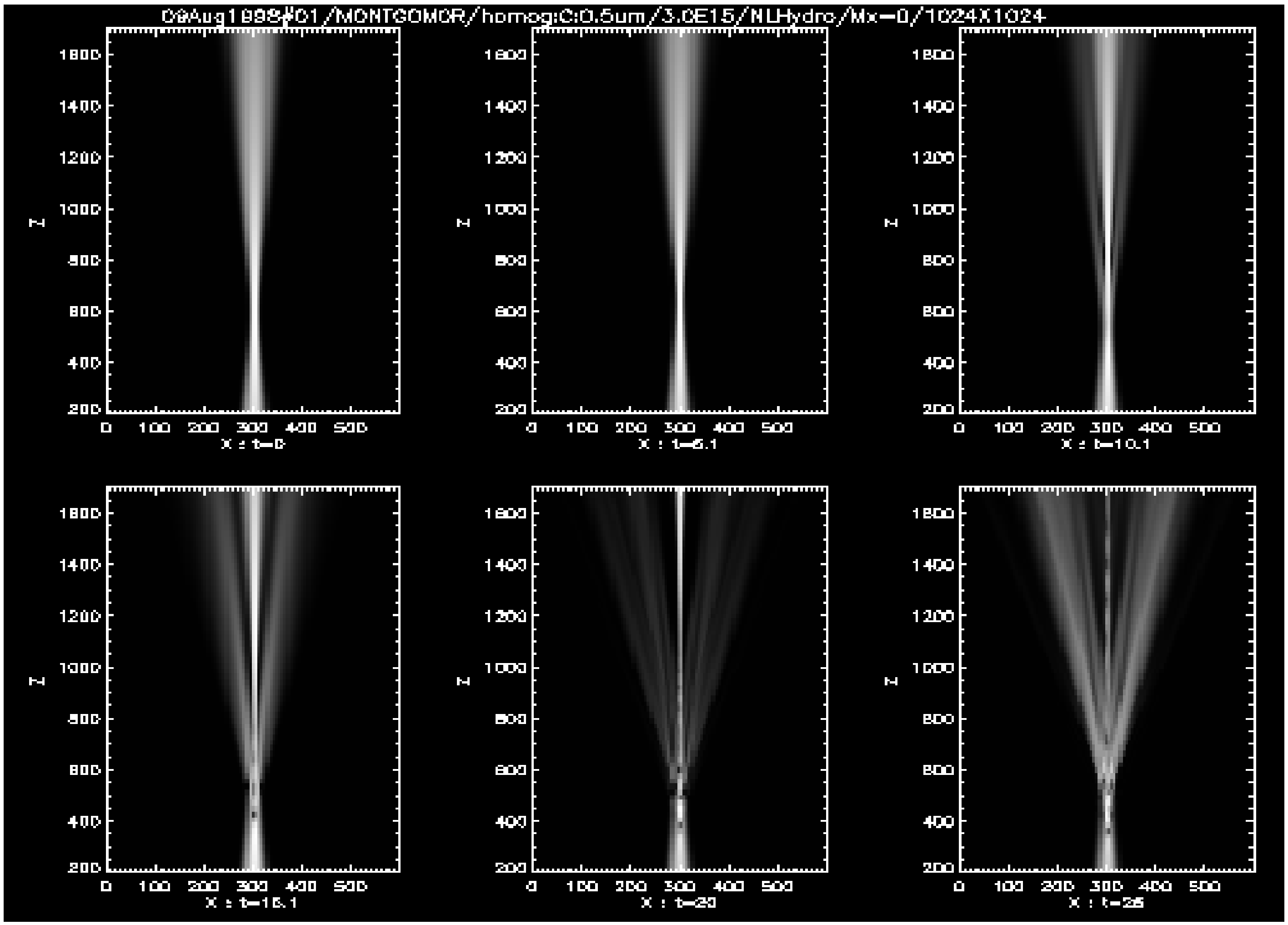


- **Plasma characteristics:**
  - **large (~ 1 mm), hot (~ 0.5 kev)**
  - **quasi-homogeneous (i.e. much longer than hot spot)**
- **backscattered SRS, SBS**
  - **reflectivity**
  - **time-resolved spectra**
- **transmitted beam angular distribution**
  - **self-focusing**
  - **beam steering in flowing plasma**
- **Imaging Thomson scattering**
  - **plasma characterization**

Los Alamos
NATIONAL LABORATORY

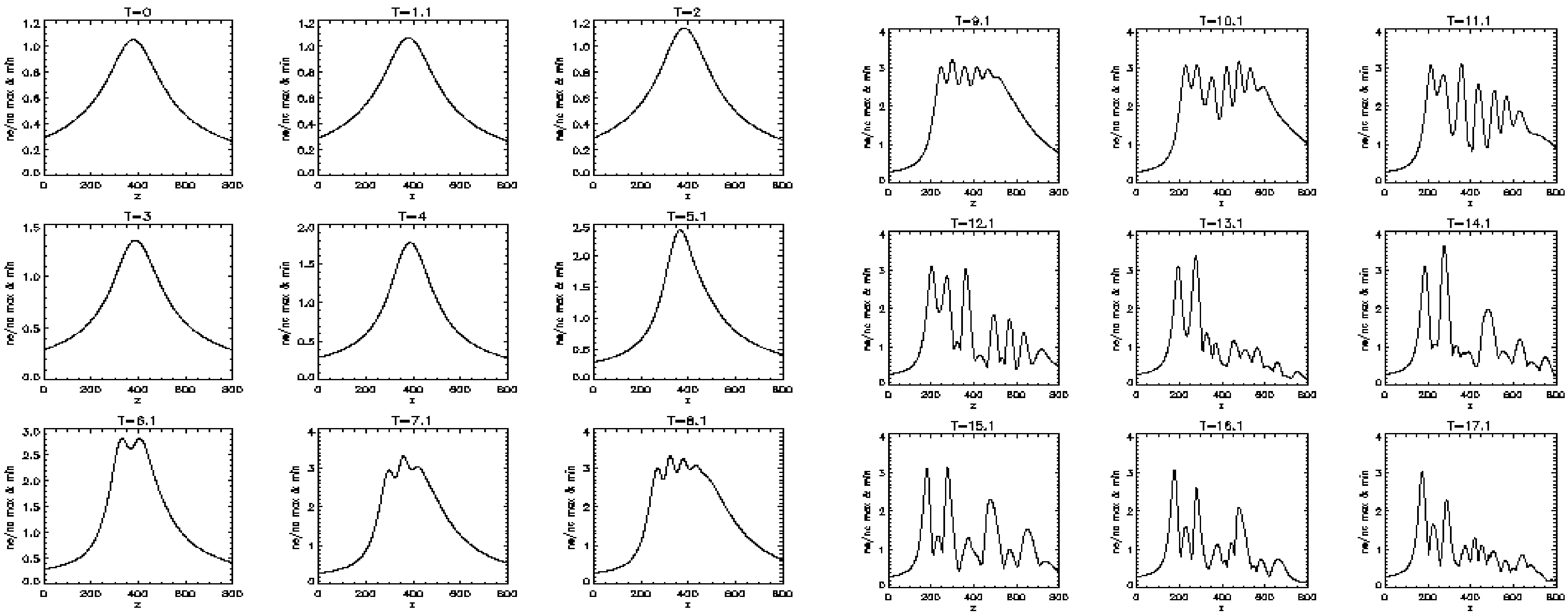
Z_{OFF} = 100 - 400 μm
to vary n_e/n_{cr}, flow

PONHF2D Simulations of Montgomery's Single f/7 Hot Spot Conditions on Trident

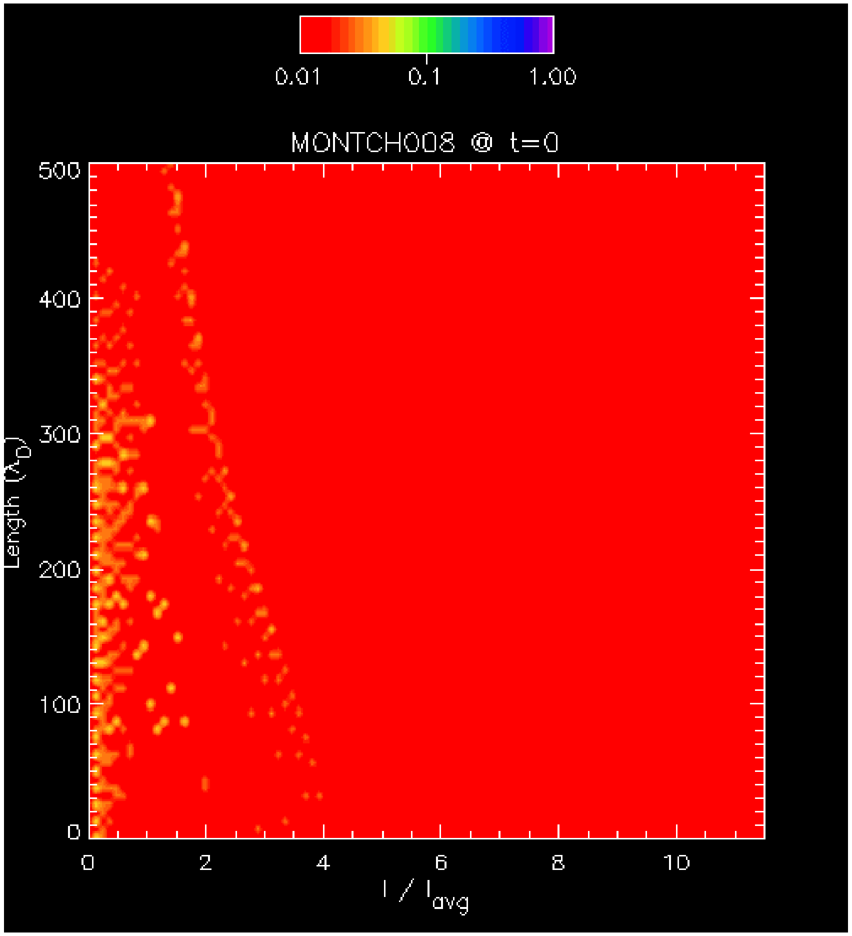


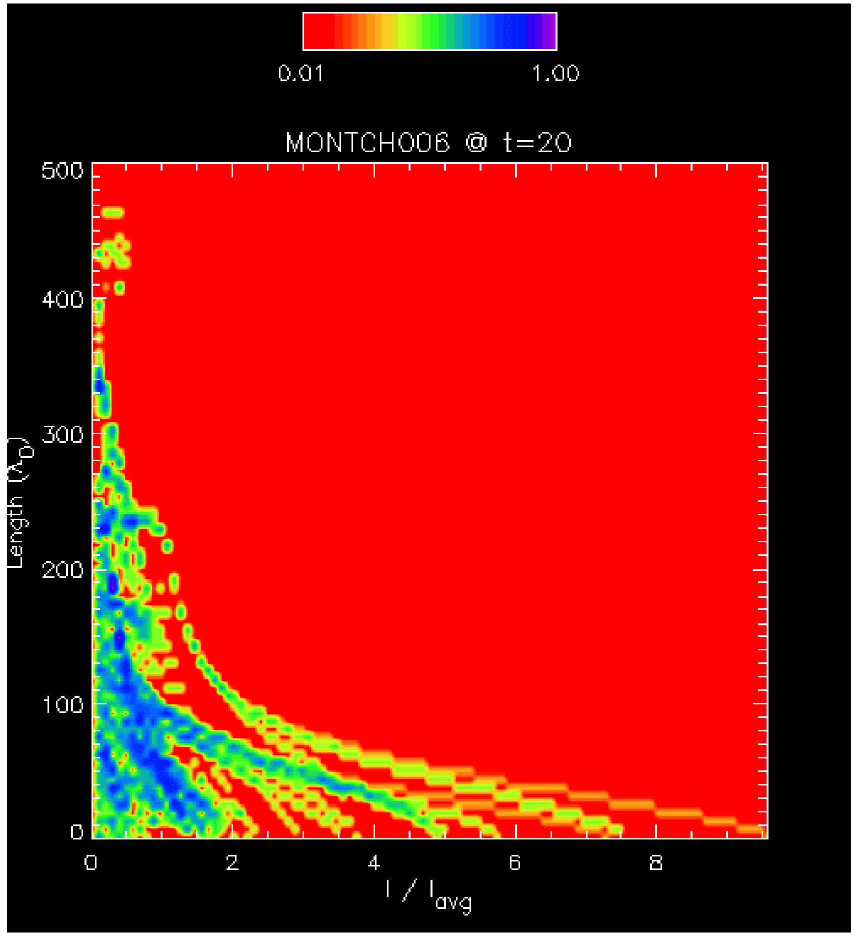
I*L Statistics Are Needed to Quantify Axial Beam Intensity Breakup Due to Filamentation

Filamentation doesn't just cause intensity spikes but spikes correlated over short Spatial (axial) intervals.



I*L Statistics in the Filamented Debris of a Single f/7 Hot Spot





Early Time Behavior of I,T and n_{DLM} Along the Axis of a SHS Beam as it Filaments Using IMPaCT

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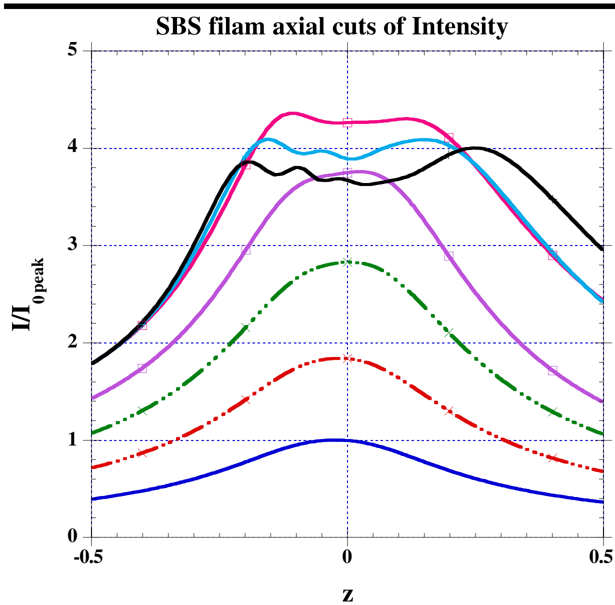
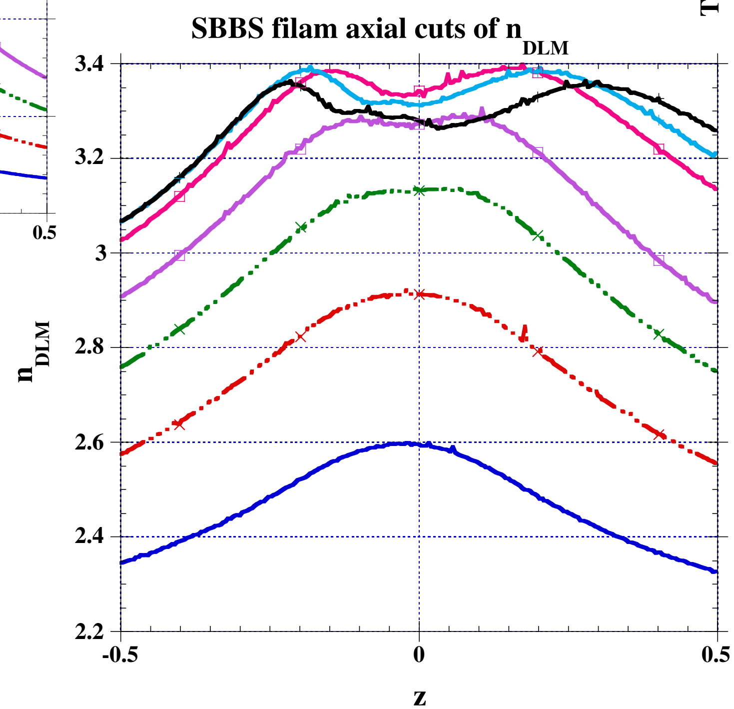
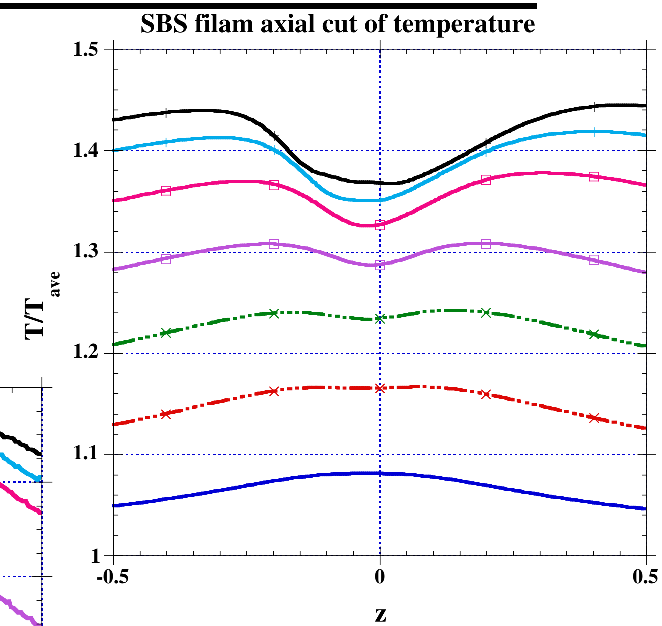


I/I_{0peak}

n_{DLM}





T/T_{ave}

Filamented Hot Spot Generates Axial Modulation of the Sound Speed (SPARK Simulations)

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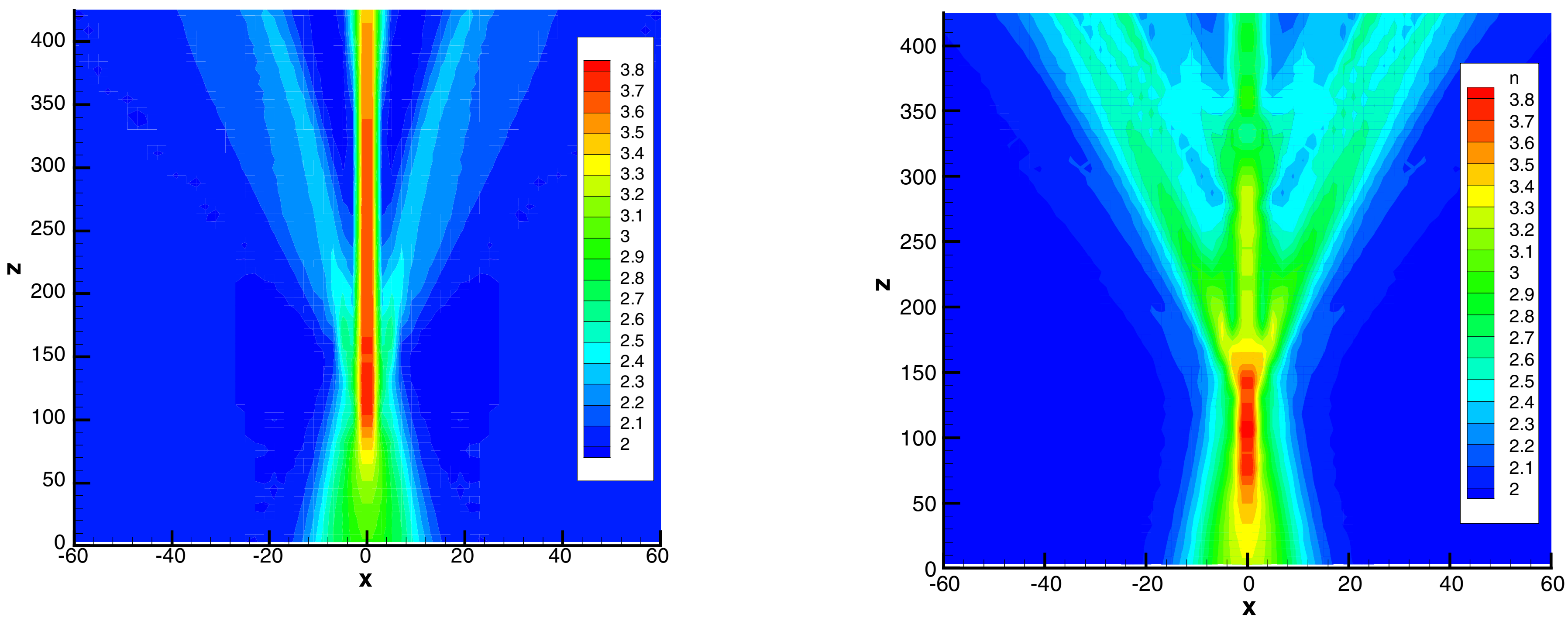
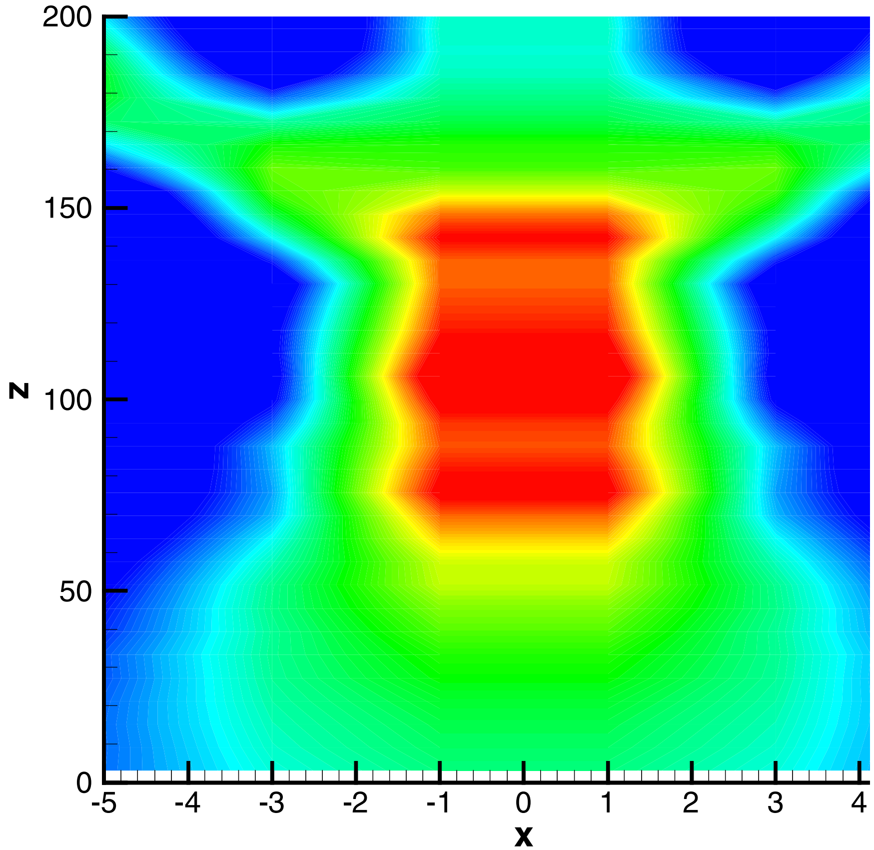


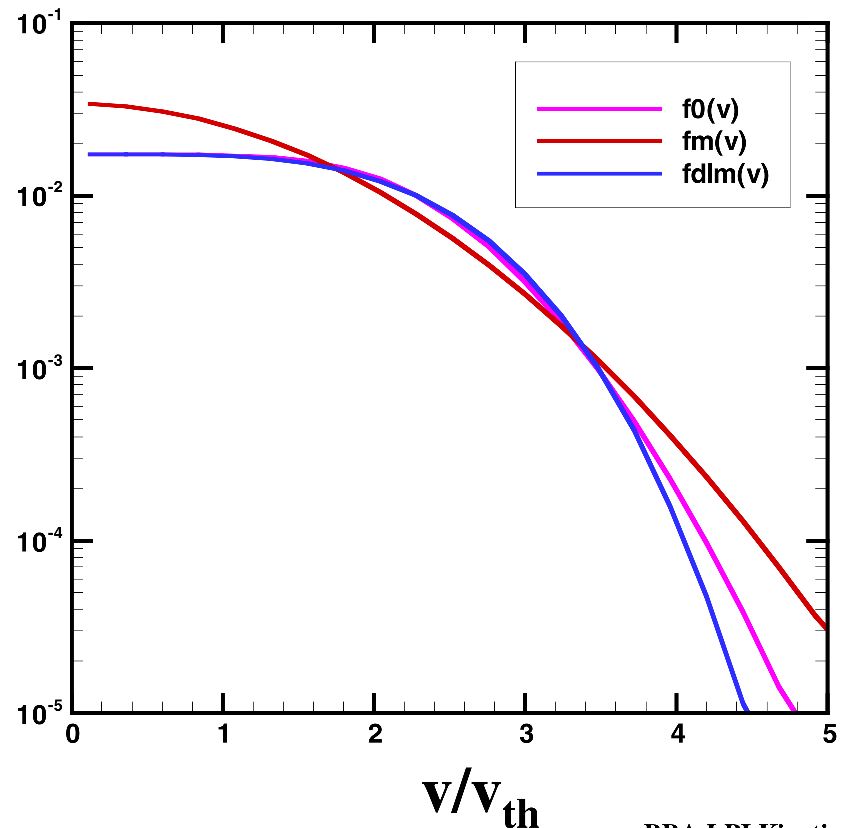
These results point to the need to run FIL and NLHT Simulations concurrently via sub-cycling.

Zooming in on the Central Hot Spot Within the Hot Spot Where $3 < n_{DLM} < 4$

(2D) ? 13 Nov 1998 ?$Al500eV 0.1nc singlehot spot$



$n_{DLM,MAX}$=3.8



The Plasma Is Heated Non-locally and Significently As the Hot Spot Filaments

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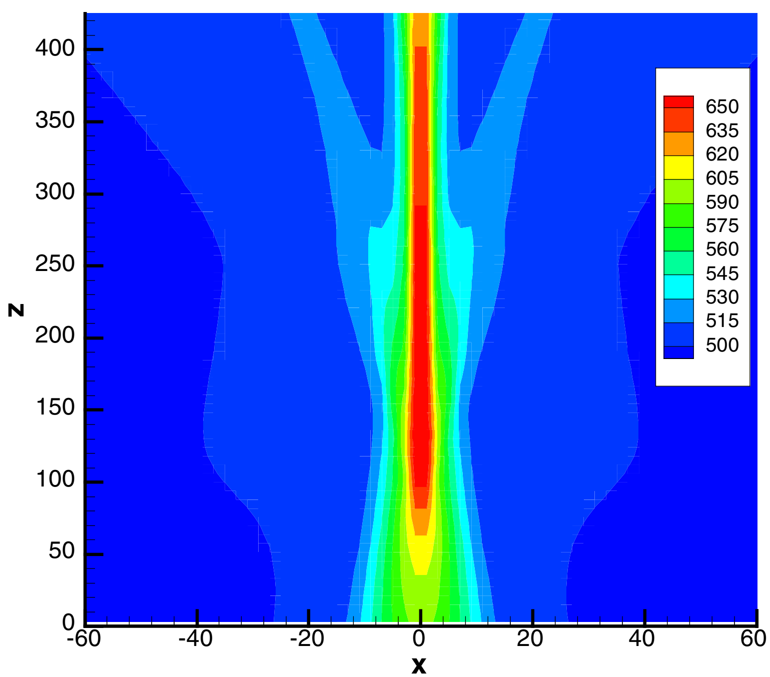

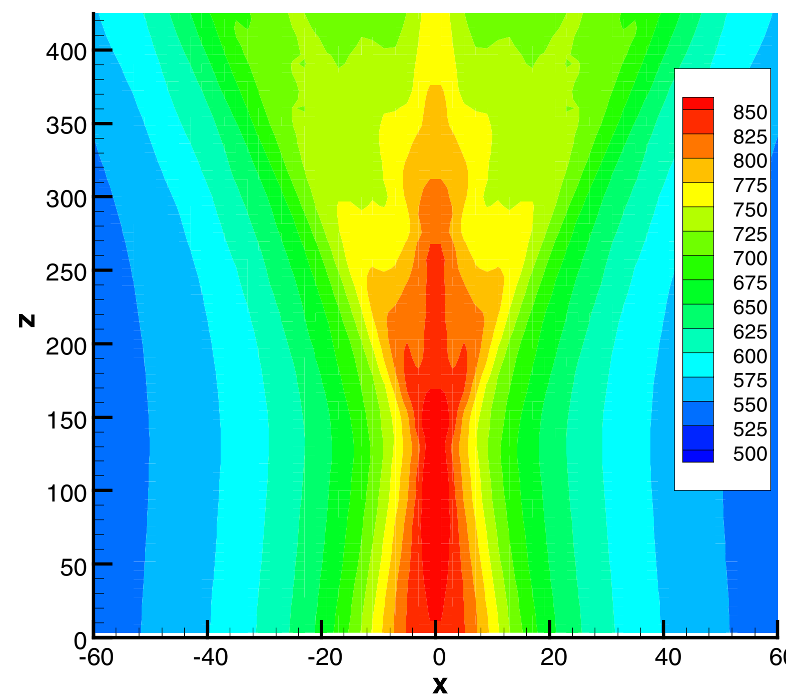

SBBS Gain Reduction in a Filamented Hot spot: Effects of I*L Statistics, the Sound Speed Boost factor, A(z), & T(z) /T_{ave}

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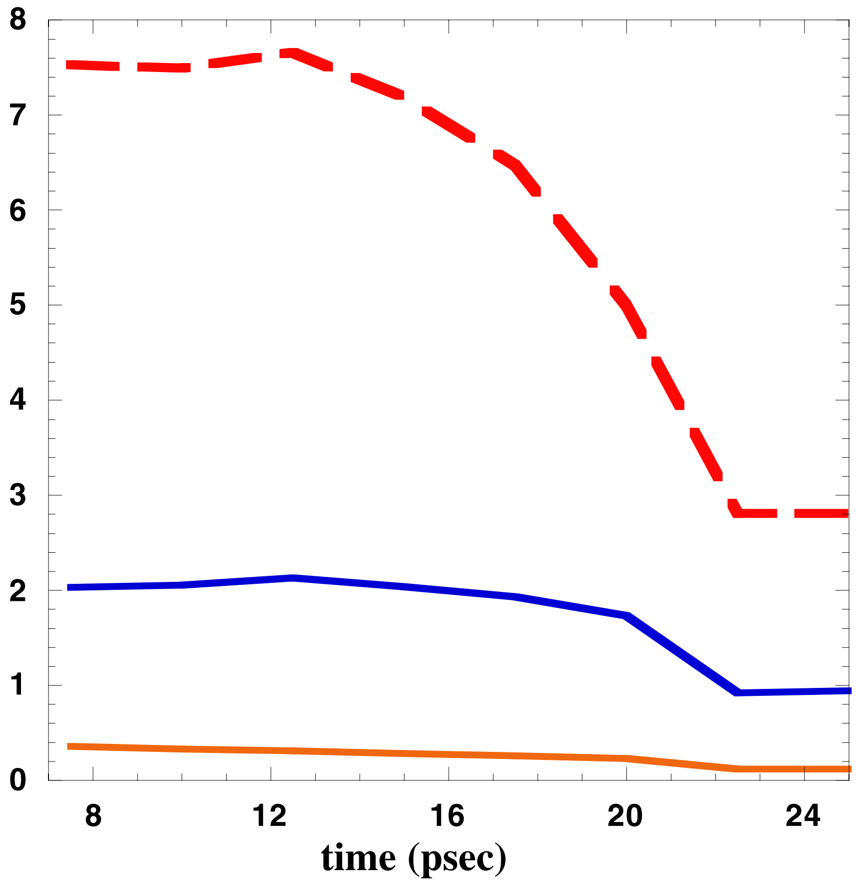

$$\frac{G_{\mathrm{SBS}}}{G_{\mathrm{SBS,MAX}}} = \mathrm{I}_G = \int_{-1/2}^{1/2} \frac{\left|\bar{\gamma}_0\right|^2(z)}{\left[1+\left(\sqrt{A(z)\left[T(z)/T_{\mathrm{ave}}\right]}-1\right)^2\right]} dz$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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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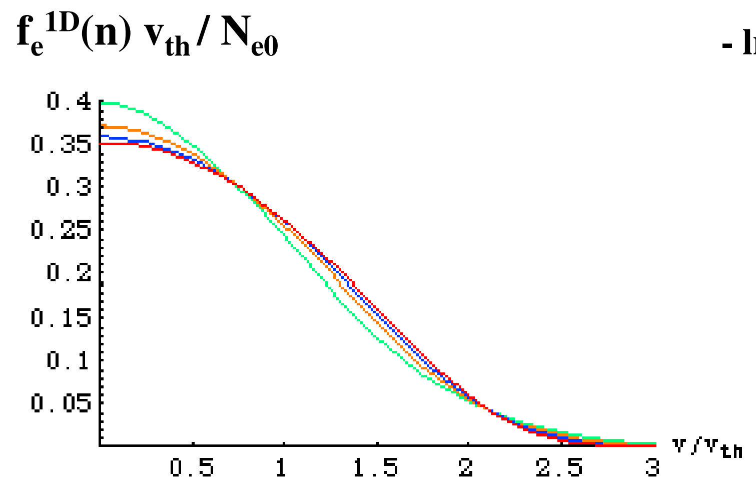

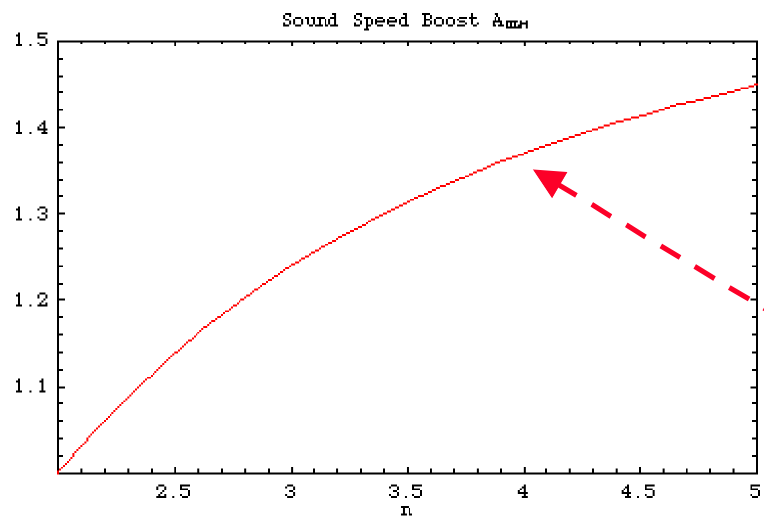

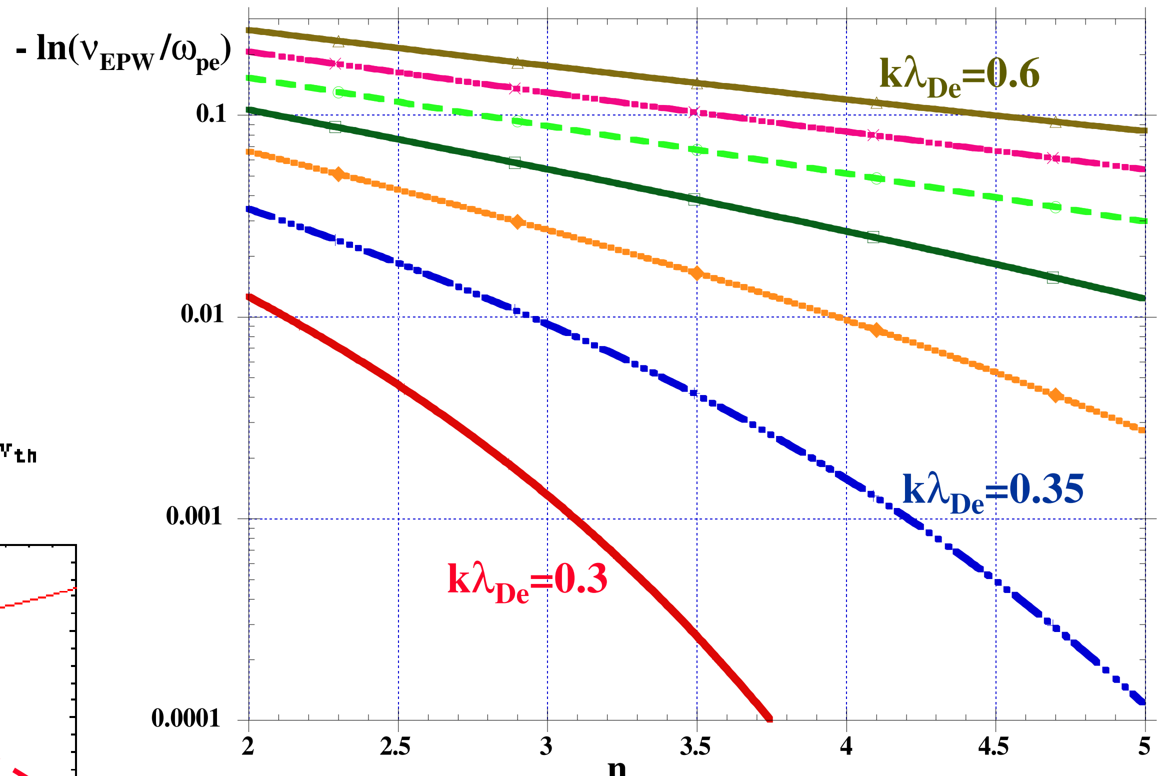

$$A_{\rm DLM}(n) = \frac{c_s^2\big|_{\rm DLM}}{c_s^2\big|_{\rm Maxwellian}} = \frac{3\,\Gamma^2(3/n)}{\Gamma(1/n)\Gamma(5/n)}$$

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

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C_8H_8, SHS f/4.5 **D. S. Montgomery et al., *Phys. Rev. Lett.*, 87, 155001 (2001)**

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

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

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

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

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

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

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

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

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

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

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

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

Self Induced and Plasmon Induced Transparency:
Exploring the Nonlinear Phase Space Physics of Plasmas via Optical Mixing Experiments

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- 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.

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 effectuate 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 Resp.

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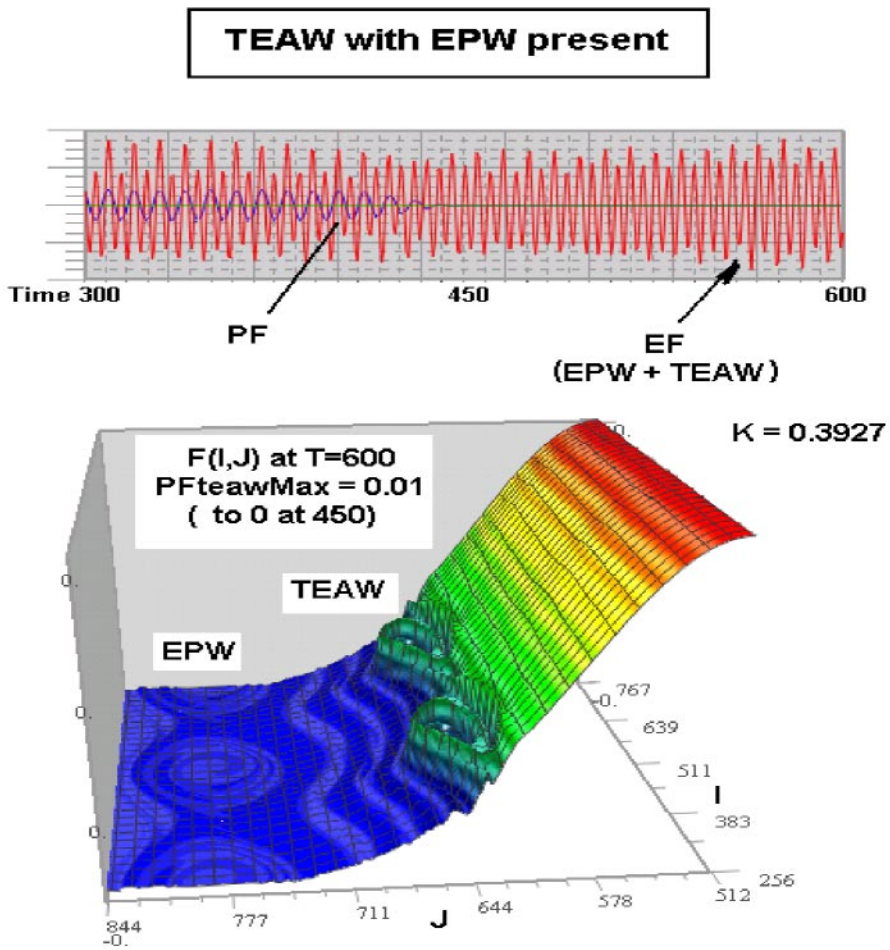

• Coexistence of TEAW and EPW after the drive of the EPW has been turned off at t=300 and after the TEAW drive has been turned off at t=450.

• 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" assertions where magical VDF distortions are induced.

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

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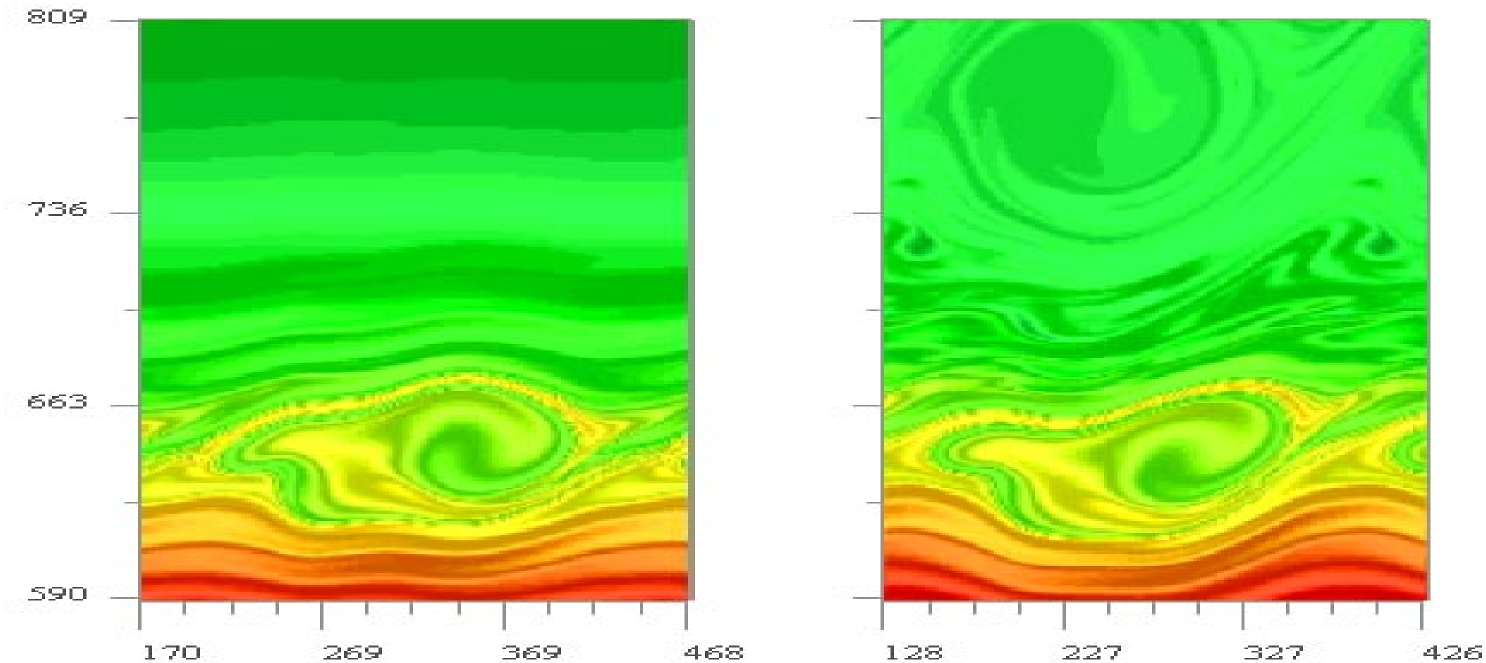
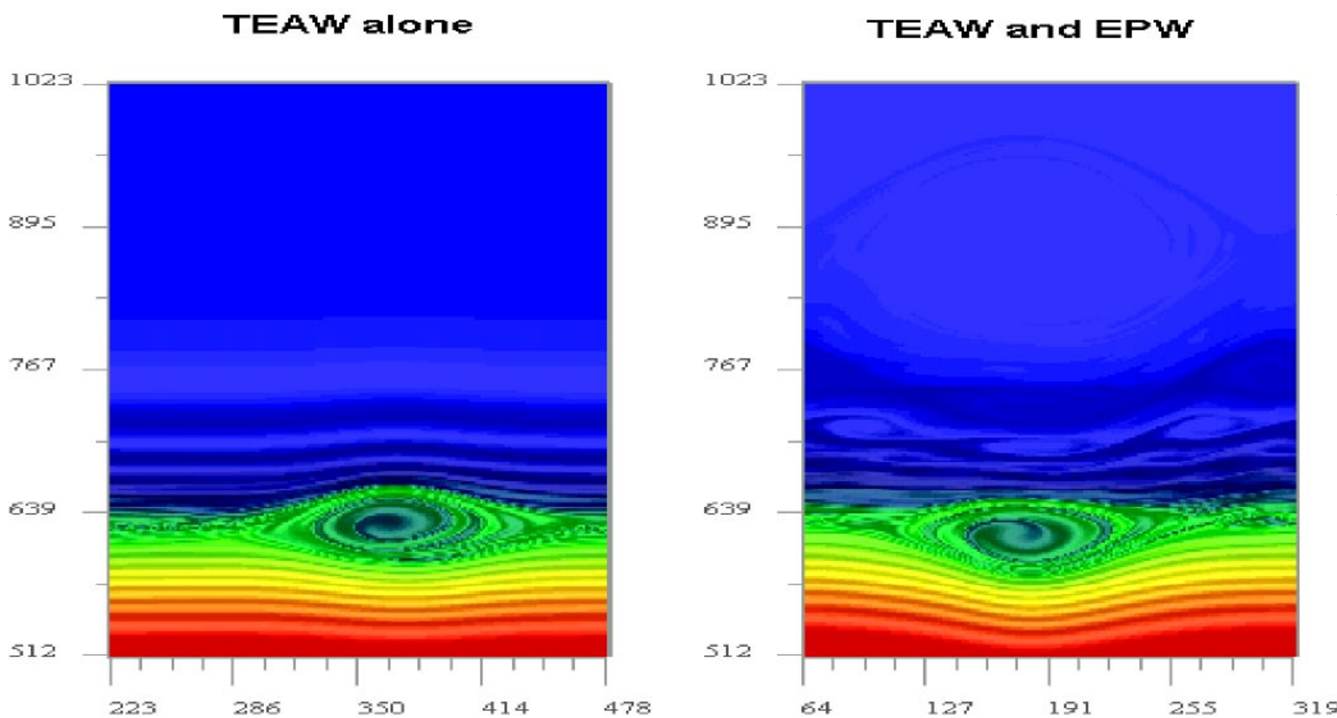
This appears to be a somewhat non-resonant case where the preexistence of the EPW does not strongly affect the TEAW.



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.

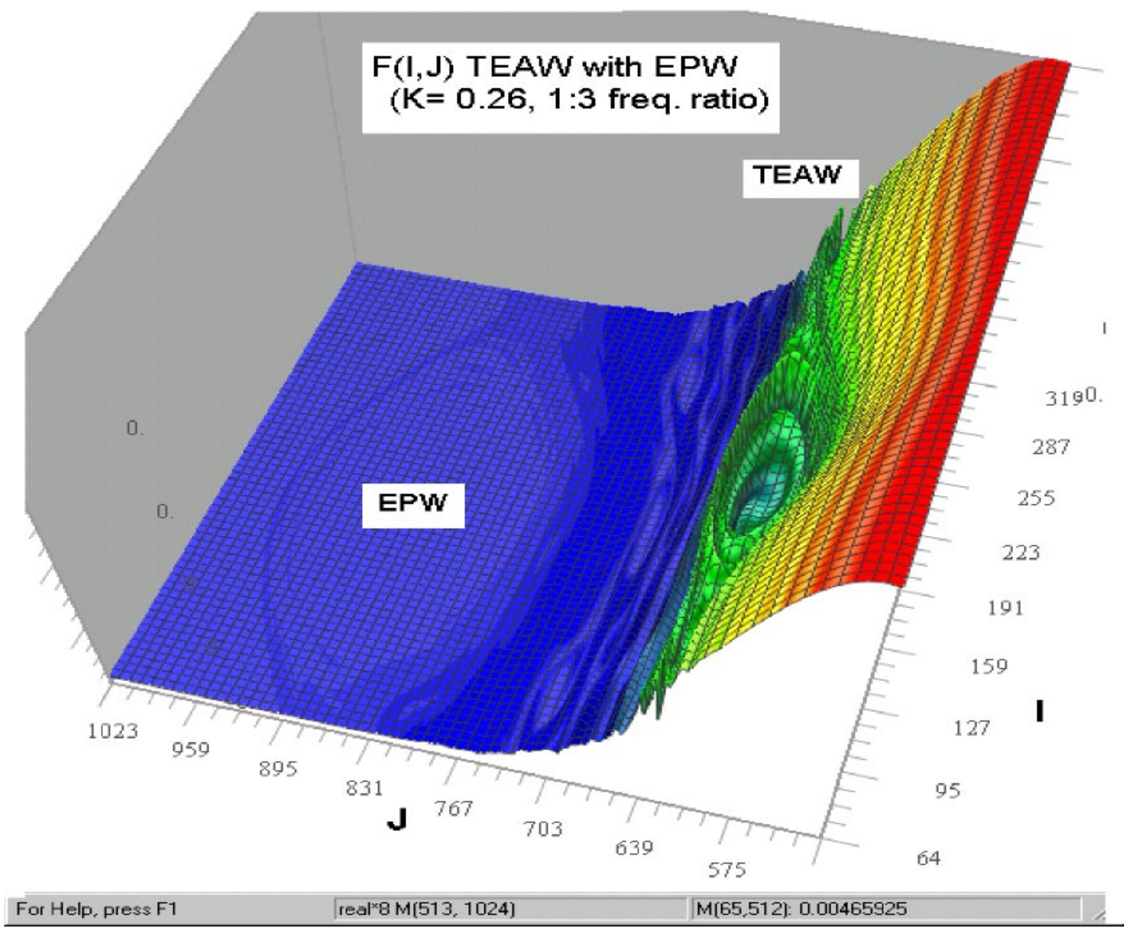


TEAW drive amplitude is higher at 0.03 while the highly resonant EPW's is 0.003.

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

See our poster [QP1.136] at APS DPP in ~ 2 weeks!

Just In Case You Did Not See the EPW Driven, Released and Present at the Scene of its Invasion South



Summary & Future Work

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- We are studying non-strictly-fluid aspects of laser-plasma interaction physics ignored by the optimist's world view that fluid models could predict the results of, and be able to explain the physics of current (past) and future LSP LPI experiments (NIF, LMJ, Omega,Nova,...)
- Focus I: Integrated studies of filamentation, NLHT and SBBS. Show reduction of SBBS gain where naïve theories predict catastrophically high levels (HTH, NIF Point Design). Include B fields, f_2, more anisotropic VDFs, larger simul.
- Focus II: Vlasov simulations to study high frequency waves and their nonlinear interactions in phase space. Self and Plasmon induced transparency physics is new and exciting from an optical mixing point of view. We will continue these simulations with our V-P and V-M codes with additional adaptive gridding capabilities, including non-uniform densities, spatially localized modes, non-Maxwellian plasmas and new experimental signatures and designs to test the flowing stream of theoretical predictions.